PRIME FARMLAND RECLAMATION

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15 Years of Progress

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TABLE OF CONTENTS

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FOREWORD

United States Department of the Interior

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RECLAMATION AND ENFORCEMENT
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JUN 01 1992

TO PARTICIPANTS IN THE 1992 NATIONAL SYMPOSIUM
ON PRIME FARMLAND RECLAMATION:

Of the natural resources protected by the Surface Mining Control and Reclamation Act of 1977 (SMCRA), none is more important than prime farmland. Recognizing that significant coal resources are in the heart of America's breadbasket, the authors of the Act made sure there were provisions for treating prime farmland with special care when coal is mined and mined land reclaimed.

Much study and debate were involved in arriving at those special provisions. There was heated controversy over whether prime farmlands could be mined at all without destroying their agricultural productivity. Some in Congress wanted a complete prohibition on disturbing such lands to get at the coal below.

The outcome in Congress was a law that allows surface coal mining on prime farmland, but only under stringent constraints that provide maximum safeguards for these vital lands.

Prime farmlands are the world's most productive because of a delicate balance of physical and chemical properties. If that precarious balance is permanently disrupted by mining, substantial loss of productivity can result. No one can tell how long it will take prime farmland soils to recover from poor reclamation. The goal of SMCRA is that with good reclamation, prime farmland will be restored to the productive capacity it had before mining.

Sound reclamation of prime farmland soils is so important that some of the most sophisticated laboratory and field research ever in the history of coal mining has been devoted to it. Top agricultural researchers in U.S. colleges and universities have been working with the coal mining industry and with government surface mining regulators to develop the best methods possible to protect prime farmland while preserving access to the coal resources beneath. That work continues.

This year marks the 15th anniversary of the passage of SMCRA. Special concern for stewardship of prime farmland during and after coal mining is stronger than ever. The 1992 National Symposium on Prime Farmland Reclamation will provide a forum for researchers to engage in the kind of information exchange necessary to assure effective prime farmland reclamation now and in the future.

Through such forums, the continuing efforts of those who are involved in this work will be available for future generations, to safeguard our ability to grow food crops without unnecessarily limiting national energy options.

Harry M. Snyder
Director

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PREFACE

The Surface Mining Control and Reclamation Act (SMCRA, Public Law 95-87) was passed in 1977 to protect the public from potential adverse effects of surface mining for coal. Among the major concerns prompting the act was the perceived need to assure that prime farmland would be restored to it's original level of productivity after mining so that the nation's capacity to produce food and to support local economies could be protected for future generations.

The Congressional Office of Technology Assessment, in the 1985 staff memorandum *Reclaiming Prime Farmlands and Other High-Quality Croplands after Surface Coal Mining* observed a critical need for additional reclamation research. It had become quite apparent that just saving and replacing each soil horizon from natural soils did not guarantee good reclamation. Substantial progress in technology development had been made, but many questions critical to success remained unanswered.

The 15 years following the passing of PL 95-87 have seen active research programs develop in several states to assess technology needed for successful reclamation of cropland. To apply this technology, however, it is important that research findings be disseminated to those who will put it to use. This symposium brings together reclamationists from industry, government, and research institutions in a national forum to present and discuss current issues related to prime farmland reclamation.

The U.S. Department of Agriculture Cooperative State Research Service, and the U.S. Department of the Interior Office of Surface Mining Reclamation and Enforcement in conjunction with the Department of Agronomy, University of Illinois, the Department of Agronomy, University of Kentucky, and the School of Natural Resources, University of Missouri, are joint sponsors of this symposium.

Sincere thanks are extended to all those who have contributed to the success of this symposium. Special thanks are due to Carol Downs, Jean Deichman, and Patricia Franzen from the Division of Conferences & Institutes, University of Illinois, and Scott Vance, Department of Agronomy, who had primary responsibilities of site arrangements, program publications, and conference registration. Appreciation is extended to the speakers for there participation in this symposium and for the quality of the manuscripts submitted to this proceedings.

In addition to committee members and authors, recognition is given to other scientists who performed critical manuscript reviews or who have agreed to serve as session moderators. Without your help this symposium and publication would not be possible.

Robert E. Dunker

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Factors Influencing Corn Grain Production on Ohio Minesoils

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Abstract. Corn production experiments in 1977 recorded low nitrogen recovery from applications at planting time. Studies from 1978-81 at three locations determined that dividing the N into planting time and sidedress applications approximately doubled nitrogen efficiency. Subsequent research compared corn production at 10 additional sites on four minesoils (Bethesda, Farmerstown, Fairpoint, and Morristown) having different depths of mixed topsoil and upper subsoil placed over the spoil. Comparisons were made to paired plots on nearby undisturbed land representative of the premined soils. Minesoil corn grain yields from 41 site-years ranged from 18 to 143 bu/acre. The mean, 74 bu/acre, was 62% of unmined soil and 80% compared to county average yields. Mined plots averaged 8% lower plant stands, had 2% higher grain moisture at harvest, and plants were 18.9" shorter in height, three indications of plant stress. Later studies determined that chisel tillage (to 14-15" depth, 30" shank spacing) increased yields only one in 13 site-years. In more limited trials, spring plowing resulted in inferior yields and delayed plant development compared to no-tillage, ripping before no-tillage, and spring disk-only tillage treatments.

INTRODUCTION

Documented changes in soil properties occur during coal mining and reclamation even though profiles now are segregated during mining (Fehrenbacher et al., 1982; Grube et al., 1974; Power et al., 1981; Smith et al., 1971). Changes that have been determined to influence crop production include soil compaction, lowered infiltration, and lowered water holding capacity. Forage establishment to minimize sediment erosion is a key component of modern reclamation. The productivity of forages in years immediately after reclamation has been evaluated (Powell et al., 1985; Underwood and Sutton, 1990).

Agriculture in Ohio's coal-producing region is primarily based on forages consumed by ruminant animals, but corn (Zea maize L.) for grain or silage is important to commercial farmers, especially those with dairy enterprises. The steep topography of this unglaciated Allegheny plateau area always has limited the land suitable for grain production. Farmers began to ask if some land reclaimed by modern procedures might be successfully used for corn production following bond release.

Corn grain production research on reclaimed land was initiated in 1977 soon after provisions of the 1972 revision of the Ohio stripmine law came into effect (Anonymous, 1972). This hallmark state legislation included requirements to grade land to approximate original contour, to return six inches or more saved soil material or equivalent over the spoil, and to promptly establish vegetative cover. Similar provisions became a part of the Federal Surface Mining Control and Reclamation Act of 1977. Although the 1972 Ohio law did not specifically address Prime Farmland (PFL), it was included in the Federal Act.

The objectives of these studies were: (1) to determine the productivity of Ohio minesoils for corn grain production and (2) to determine how different management practices and environmental factors affect yields.

Experimentation conducted in five counties during the 11-year interval (1977-1987) was divided into four phases that reflected different major research objectives:

Phase 1 - Preliminary 1977-78 studies at one site, followed by more detailed 1979-81 experiments at two other locations, sought to define key management practices to successfully grow corn on Ohio's reclaimed land. A primary objective was to determine ways to achieve adequate, season-long nitrogen nutrition. Reference plots on nearby undisturbed land were included.

Phase 2 - This phase spans the entire 1977-87 interval with paired mined-unmined plot comparisons at 13 sites in five counties with four minesoils. These sites had a range in depths of soil material placed over the spoil. Ten additional sites were added to the initial three in or after 1982, and cropped for up to five seasons to allow the study of the effects of different weather patterns.

Salaries and research support were provided by state and federal funds appropriated to OSU-OARDC. Journal Article No. 40-92.

These 10 new locations, plus selected data from Phases 1, 3, and 4, permitted comparisons of 41 site-years data (sites x years cropped).

Phase 3 - Trials during 1984-85 utilized portions of Phase 2 sites in Belmont County to evaluate 14-15 in chiseling (ripping). Possible second-year effects were also studied. Researchers in Illinois (Jansen, 1981) and in Kentucky (Barnhisel et al., 1979; Huntington et al., 1980) had shown positive yield and plant growth responses from ripping, particularly where pan scrapers were used in reclamation (Powell et al., 1985). Scrapers are the main means of transporting soil in Ohio reclamation.

Phase 4 - Three 1986 field experiments compared four tillage methods: (1) no-tillage, (2) fall ripping, (3) spring plowing and disking, and (4) spring disking only. Corn was planted again at two of these sites in 1987. Most treatments were repeated except for fall ripping.

MATERIALS AND METHODS

Soils Information

Experimental sites were selected from four Ohio minesoils: Bethesda (loamy skeletal, mixed, acid, mesic), Farmerstown (fine loamy, mixed acid, mesic), Fairpoint (loamy skeletal, mixed, nonacid, mesic), and Morristown (loamy skeletal, mixed (calcareous), mesic) (Rubel et al., 1981; Seaholm and Graham, 1991). All are Typic Udorthents. Table 1 presents minesoil characteristics.

Previously all experimental sites had been classified as either Bethesda, Fairpoint, or Morristown and this nomenclature used in prior papers (Underwood et al., 1981; Underwood and Sutton, 1985). In 1987, a new non-prime minesoil series, the Farmerstown was established in the Holmes County Soil Survey. It now appears that this series is more appropriate for five former Fairpoint and Morristown sites, since they greatly exceed prescribed depths for topsoil cover over the spoil for Fairpoint or Morristown. The five do not fully meet Farmerstown series criteria since their spoils have higher pH than a typical Farmerstown. Thus, the 13 sites now have two with Bethesda, five with Farmerstown, three with Fairpoint, and three with Morristown minesoils.

One of the 13 corn test sites was reclaimed to Prime Farmland standards. In Ohio, only 0.67% (1144 acres) of the 170,000 acres affected by surface mining between January 1978 and March 1986 were under permit as PFL. This approximate rate has continued since 1986.

Soil samples were tested from all sites to determine nutrient element status and to formulate fertilizer programs. Soil profiles from many sites were evaluated for physical and chemical properties by the OSU Soil Characterization Laboratory.

General Crop and Site Information

Corn was planted at most sites using no-tillage planters even though some were planted in tilled seedbeds. Soil and above-ground insects were controlled with lindane or diazinon seed treatments and granular terbafos or carbofuran applied by planter in the furrow. Methiocarb was sometimes also applied to seed to reduce predation by birds and/or rodents. Eleven commercial hybrids selected for high yield potential, seedling vigor, good stalk strength, and flexible ear size

Table 1. Description of the four Ohio minesoils.

	Bethesda	Fairpoint	Farmerstown[1]	Morristown
Reaction	pH 3.6-5.5	pH 5.6 - neutral	pH 5.6 - neutral	Calcareous
Particle-size class	Loamy-skeletal[2]	Loamy-skeletal	Fine loamy	Loamy-skeletal
Typical fragments	Sandstone or siltstone, shale, carbonaceous shale	Shale, sandstone, siltstone, few limestone	Sandstone, siltstone, and shale	Limestone, shale, siltstone, sandstone
Typical color of fines	Yellowish brown	Light brownish gray, brown, gray	Dark gray	Dark gray
Mineralogy	Mixed	Mixed	Mixed	Mixed
Organic carbon in replaced A or AB	0.5-1.2	0.5-1.2	0.7-1.6	0.5-1.2

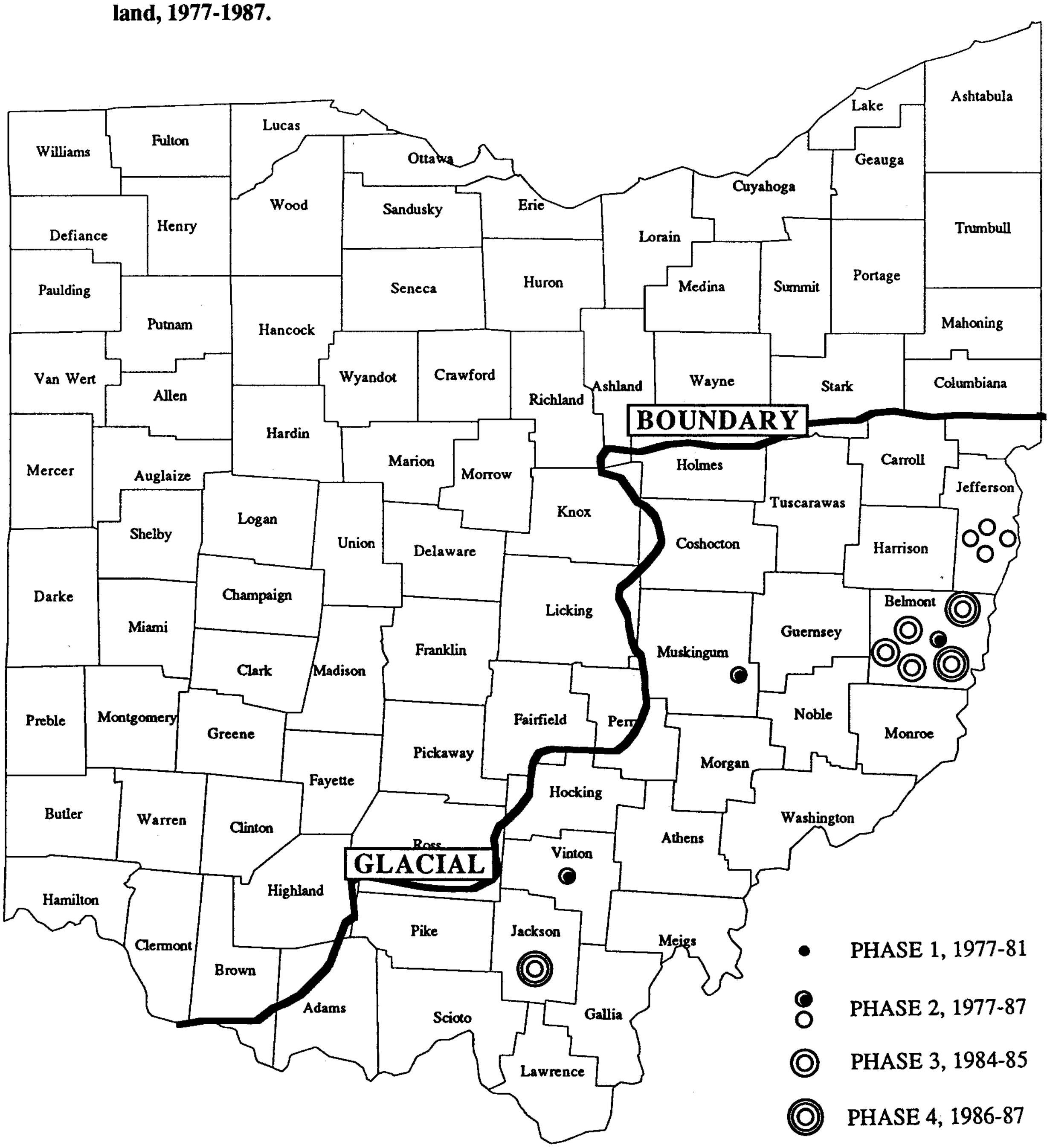
[1]Farmerstown soils on these plots have a higher reaction in the substratum (2C horizon) than is defined as the range for the series. This difference, however, does not significantly affect the use or management of the soils.
[2]Skeletal: rock fragments 2mm in diameter or larger, >35% by volume.

were utilized. More than half site-years were planted with five hybrids. Weed control with no-tillage was achieved using pre-emergent broadcast applied combinations of burndown and residual herbicides. Mixtures of residual herbicides were used where soils were tilled. All yields are reported as shelled corn grain, 15.5% moisture basis.

Adequacy of plant nutrition was determined by (1) Kjeldahl N and spectrographic analyses of ear leaf blade samples taken at green silk stage and by (2) Kjeldahl N analyses of grain at harvest. Plants in both reclaimed and undisturbed portions of experimental sites generally met recognized criteria.

Figure 1 shows approximate location of the 13

Figure 1. Location of experimental sites for Ohio corn production studies on reclaimed surface mined land, 1977-1987.



research sites in Belmont, Jackson, Jefferson, Muskingum and Vinton counties. The solid dot symbol shows where initial experiments were conducted in Muskingum County during 1977 and 1978 on land reclaimed in 1974. Ten acres of corn were no-tillage planted into heavy grass-legume sod. A small plot replicated nitrogen rate trial compared four rates of nitrogen, all applied at planting time, using ammonium nitrate. Ten acres were planted in 1978 into both corn stalk ground and adjacent sod. Another nitrogen rate study evaluated rates of N all applied at planting and in split applications with half applied at planting and the remainder side-dressed four to five weeks later. This site had a high clay content in the topsoil that often caused poor closure of the planter slit and resultant inadequate corn stands. It was decided that future studies would be conducted at locations with topsoil of silt loam texture.

The solid dots also show where the Belmont and Vinton Phase 1 studies were conducted from 1979-81. Replicated studies were conducted at each location for three years using the same plots to compare nitrogen rates and times of application. Initially no-tillage corn was planted into heavy grass-legume sod; then into corn stalks the following two years. Rates of N were 0, 100, 200 and 400 lb/acre all at planting. Also split application treatments of 50 + 50, 100 + 100, and 200 + 200 lb/acre with one-half at planting and the remainder side-dressed.

Small open circles in Figure 1 indicate experimental sites added after 1982. They were generally 0.5 acre or larger for the mined component. The comparable sized plantings on a nearby unmined reference plot represents soil type present in the mined area before disturbance. Unmined areas were directly adjacent or within a 2000 ft. distance. Corn production practices incorporated experience gained from previous trials, including use of split-applied nitrogen from ammonium nitrate at approximately 200 lb/acre rate. Sidedressing was accomplished 4-5 weeks after planting.

New locations were usually in sod and frequently corn was planted no-tillage directly into the sod. In other cases, the sod was plowed and disked for planting into tilled soil. Subsequent crops were planted no-tillage into corn stubble or plowed and disked when farmed conventionally. Weed control was generally excellent and soil and above ground insects were not a problem. Data from no-tillage planted treatments from Phases 3 and 4 were utilized in Phase 2 summaries.

Map symbols of increasingly larger circles locate Phase 3 and Phase 4 sites in Figure 1. They represent continued, more intensive experimental use of certain Phase 2 locations. Corn production management paralleled practices previously described except for the tillage variables introduced into these studies.

The 14-15 in chiseling or ripping of split-plot portions at the five Belmont sites in spring 1984 and at three (2-Belmont, 1-Jackson) Phase 4 sites in October 1986 were accomplished using heavy-duty farm chisels. Equipment had 24-inch long, curved, subsoiler shanks spaced 30 inches apart. Shanks were set to penetrate 14 to 15 inch deep into the soil-spoil. Soil moisture conditions at sites in spring 1984 and in October 1986 were low and considered near optimum for proper ripping action.

Experimental Design and Analyses

Most of these experiments utilized randomized complete block designs with three or four replications. Analysis of variance was used to evaluate yield, tissue nutrient status, and measures of plant development. Many Phase 2 sites consisted of paired, nearby non-replicated one-half acre or larger plantings of corn in mined and unmined soils. Four randomly selected 1/196 acre sized areas were harvested in each to provide estimates of yield and plant development. For analysis, each location-year was considered a random environment. Simple correlation and multiple regression analyses were also utilized to study portions of the data.

RESULTS AND DISCUSSION

Phase 1 - Table 2 presents three years yield data from the Belmont site and two from the Vinton site. These studies were initiated after the 1978 Muskingum trial indicated greater N efficiency with split applications. Yields from 50 + 50 lb/acre rates of N were very comparable to 200 lb/acre (2X) when all applied at planting, and 100 + 100 lb/acre rate split-applied very comparable to 400 lb/acre (2X) all applied at planting time. The 1979 corn yield data from the Vinton site were not included because simultaneous urea and lime applications caused extreme N loss. This was indicated by low nitrogen N content in leaf tissue and grain and negligible yield response to N fertilization rates.

The Belmont Phase 1 site has a Farmerstown minesoil with 36 in total AP, B/A and B/C material over the spoil and represents superior reclamation under the 1972 Ohio law. The Vinton site with Bethesda minesoil has only 4 in replaced natural soil and was forested prior to mining. The limited topsoil, acidic spoil, high bulk densities (surface downward - A-1.55, C2-1.73, C3-1.87), lower available soil moisture plus poor rate of saturated infiltration resulted in a minesoil with lower potential for corn production. Surface soils at both sites were silt loam texture and corn stands from 18,500 to 20,500 plants/acre were consistently achieved.

Table 3 gives monthly precipitation May-September that indicates all three seasons in Belmont County and the 1980 season in Vinton County exceeded the 21-23 inch May-September long-term average. The 1981 season at Vinton began with adequate rainfall through June, then a late July-September drought severely reduced yields. These Vinton trials provided first indication Bethesda spoils were inferior to others for corn. Table 4 presents ear-leaf and grain analyses which further demonstrate the superior efficiency from split applications of nitrogen. Lower organic matter in reconstructed minesoils and greater denitrification in saturated slow infiltration rate minesoils are two prob-

Table 3. May-September Monthly Precipitation, Belmont and Vinton County Sites, 1979-81.

	Belmont*			Vinton*	
	1979	1980	1981	1980	1981
	(inch)	(inch)	(inch)	(inch)	(inch)
May	7.0	5.7	4.2	2.4	6.1
June	2.6	4.7	11.7	5.3	5.2
July	3.9	8.5	4.4	11.2	3.5
August	7.1	12.3	1.8	7.6	1.1
September	5.5	1.7	4.1	1.3	1.8
	26.1	32.9	26.2	27.8	17.7

*regional long-term mean precipitation - 21 to 23 inches (May - Sept.).

Table 2. Influence of Nitrogen Fertilizer Rates and Application Times on Corn Grain Yields Belmont and Vinton County Sites, 1979-81.

	1979	1980		1981	
N APPLIED	Belmont	Belmont	Vinton	Belmont	Vinton
(Lb/A)	(Bu/A)	(Bu/A)	(Bu/A)	(Bu/A)	(Bu/A)
O-Check	64	23	33	58	22
100 at planting	86	60	45	87	20
200 at planting	105	80	76	110	32
400 at planting	127	94	97	141	33
50 + 50 split applic[1]	115	80	71	98	48
100 + 100 split applic	121	92	91	148	33
200 + 200 split applic	138	110	72	141	27
$LSD_{(0.5\%)}$	26	43	34	24	NS
CV (%)	13	32	28	12	30
Unmined Reference Plots[2] (not replicated)					
O-Check	125	90	N/A	103	129
400 at planting	150	143	N/A	124	154

[1]50% broadcast at planting time, and 50% sidedress 4 to 5 weeks later.
[2]Lowell silt loam (fine, mixed mesic Typic Hapludalfs) for Belmont; Orville silt loam (fine-loamy, mixed, nonacid, mesic Aeric Fluvaguents) for Vinton.

Table 4. Percentage Nitrogen in Ear Leaf Tissue and Silking and in Harvested Grain as Influenced by Nitrogen Fertilizer Rates and Application Times, Belmont and Vinton County Sites, 1979-81.

	Ear Leaf (>2.75% adequate)					Grain (>1.30% adequate)				
	Belmont			Vinton		Belmont			Vinton	
N Applied	1979	1980	1981	1980	1981	1979	1980	1981	1980	1981
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
O-Check	2.56	1.80	2.61	1.78	1.88	1.21	1.11	1.07	1.10	1.11
100 at planting	2.68	2.37	2.21	2.30	2.26	1.41	1.16	1.15	1.05	1.25
200 at planting	3.00	2.64	3.02	2.78	2.47	1.35	1.35	1.23	1.27	1.25
400 at planting	3.33	3.00	3.33	2.85	3.03	1.52	1.52	1.43	1.32	1.66
50 + 50 split applic*	3.14	2.59	2.99	2.40	2.91	1.45	1.34	1.17	1.13	1.41
100 + 100 split applic	3.45	2.83	3.02	2.69	3.10	1.58	1.39	1.46	1.22	1.57
200 + 200 split applic	3.30	3.19	3.51	2.79	3.36	1.64	1.53	1.48	1.35	1.72
$LSD_{(0.5\%)}$	0.20	NS	NS	0.43	0.30	0.52	0.18	0.21	0.14	0.16

*50% broadcast at planting time, and 50% sidedressed 4 to 5 weeks later.

able reasons why application of all N at planting time is less efficient. Losses in runoff from high-intensity precipitation shortly after application may occasionally become important.

Phase 2 - Corn production from 41 site-years derived from 13 locations between 1977-87 were compared in regards to yield, harvest stand, plant height, and grain moisture at harvest. The mean yields were 74 (range 18-143) bu/acre for reclaimed plots, 119 (range 65-160) bu/acre for undisturbed plots, and 93 (range 66-121) bu/acre for county average yields from Ohio Agricultural Statistics Service. The reclaimed mean yield was 62% of the unmined plot mean and 80% of the mean of county average yields. Soil profile data indicates lower organic matter and generally higher bulk densities with minesoils. These differences had a more pronounced negative effect on minesoils during growing seasons with low available soil moisture.

Harvest stand mean was 8% lower for corn grown on minesoils vs undisturbed. Means were 19,759 (range of 12,348-26,721) plants/acre for reclaimed plots, and mean of 21,581 (range 15,333-26,264) plants/acre for undisturbed sites.

Plant heights on minesoils averaged 18.9 inches shorter and grain 2% higher in harvest moisture. Plant height mean was 93 inches (range 75-114) for reclaimed and 112 inches (range 95-137) for undisturbed. Grain moisture reclaimed mean was 30.7% (range 16.8-49.3) and 28.7% (range 17.7-44.2) for undisturbed. Researchers consistently observed another measure of delayed plant development when procuring ear-leaf samples at green silk stage. Plants grown on unmined soil were several days ahead in silk and tassel emergence than plants grown on minesoils.

Multiple regression analysis of 27 site-years 1977-84 had shown that depth of replaced soil over spoil was the most important and consistent factor influencing yield, stand, grain moisture and plant height (Underwood and Sutton, 1985).

Table 5 summarizes soil and yield data from the five Farmerstown sites with considerable replaced soil over the spoil. This data indicate that greater topsoil depth alone will not insure high grain yield. Yields over 100 bu/acre are underlined.

Three Farmerstown sites did account for five of eight instances within the 41 site-years in which >100 bu/acre yields were achieved. Two of three other 100+ yields were from another Jefferson County location on a Fairpoint minesoil having 15 in of topsoil. Yields here were 111 bu/acre in 1983 and 108 bu/acre in 1984. The eighth 100+ yield was from Jackson County in 1984 on a Fairpoint minesoil with seven inches topsoil over spoil. These three instances occurred where precipitation was adequate and well distributed through the

Table 5. Soil and Yield Data from Five Ohio Farmerstown Minesoil Sites.

Location	Replaced Soil Total Depth (inches)	Replaced Soil Horizons & Depth	Year	Yield (bu/A)
Belmont Co.	36	AP - 6	1979	<u>138</u>**
(Pickenpaugh)*		B/A - 10	1980	<u>108</u>
		B/C - 20	1981	<u>143</u>
Jefferson Co.	32	AP - 5	1982	<u>104</u>
(Rector A)		C1 - 24	1983	41
		C2 - 3+	1984	83
Jefferson Co.	23	AP - 5	1982	<u>109</u>
(Rector B)		C1 - 18	1983	56
Belmont Co.	46	A - 9	1983	38
(Wise)		B/A - 12	1984	69
		C1 - 25	1985	75
Belmont Co.	40	NOT	1983	46
(Kinder)		DETERMINED	1984	93
			1985	75

* Property owner name.

** > 100 Bu/A yields are underlined.

season. The disappointing 1983 yields at the Wise and Kinder sites influenced the decision to include 14-15 in chiseling (ripping) into portions of Belmont sites during 1984. The Wise location in Belmont County is the only one of the 13 corn test sites reclaimed to Prime Farmland standards. Pedologists associated with these studies suggest that (1) higher clay content and (2) compaction from equipment and perhaps the movement of replaced material when it was too wet were probable reasons for inferior yields at these two locations (personal communication).

The important role of seasonal precipitation (amount and distribution) is difficult to prove without methods such as modeling; however, simple correlations of 21 sets of data were calculated where good precipitation data existed. Undisturbed soil yields correlated with May-September precipitation with r=0.583 (P=0.01%), whereas minesoil yields had a lower correlation r=0.423 (P=.10%).

Farmerstown, Morristown, and Fairpoint outperformed the droughtier Bethesda minesoil for corn production. Soil characterization indicated that the Bethesda had the lowest available moisture in the plant root zone. Lower plant population, delayed seedling emergence, reduced plant height, and higher grain moisture with all minesoils, indicated overall greater stress on plant growth on minesoils compared to production on unmined soils. Plant tissue spectrographic and Kjeldahl N analyses of leaf and grain indicate no special problems with primary, secondary, or micronutrient element nutrition with split application of N.

Phase 3 - Yield was only significantly improved in 1984 from ripping at one of five locations. Grain harvest moisture was significantly lower there too, an indication of more rapid plant development from ripping. None of the three sites replanted again in 1985 to corn showed any residual responses from the 1984 ripping. Chiseling had no effect on stands or nitrogen in harvested grain either season at all sites.

Phase 4 - Table 6 summarized 1986-87 studies comparing chiseling, no-tillage, spring disking, and spring plowing. Significant tillage effects were only consistently obtained at the Belmont site with Morristown minesoil with 14 in topsoil over the spoil. There the spring plowing treatment had a lower yield, stand, and plant height, and a higher grain moisture at harvest. Ripping, no-tillage, and spring disking were equal in these measures of yield and plant growth. No statistical differences occurred at Jackson either year. Only one measure of plant response was significant in 1986 at the Belmont site with Farmerstown minesoil and 46 in soil over the spoil. Plant height was reduced

Table 6. Summary of grain yield, stand, moisture in grain and plant height, Ohio tillage studies on reclaimed surface mined land, 1986-87.

	Yield	Harvest Stands	Moisture on Grain at Harvest	Plant Height
	(Bu/A)	(000/A)	(%)	(inches)
Site 1 (Morristown minesoil - Belmont County, 2 yr.)				
	87.7A rip	19,233A rip	27.9A sp plow	105.9A rip
	84.3A no-til	19,183A sp disc	26.0AB sp disc	104.6A no-til
	73.1A sp disc	18,228AB no-til	25.8B rip	101.3A sp disc
	50.1B sp plow	17,003B sp plow	25.7B no-til	87.8B sp plow
$LSD_{(0.5\%)}$	20.9	1931	2.0	8.0
r^2	.87	.94	.73	.96
CV	20%	15%	7%	4%
Site 2 (Fairpoint minesoil, Jackson County, 2 yr.)				
		No significant differences.		
Site 3 (Farmerstown minesoil, Belmont County, 1986 only)				
	NS	NS	NS	106.7A no-til
				104.0A rip
				103.0A sp disc
				93.5B sp plow
$LSD_{(0.5\%)}$				8.5
r^2				.68
CV				5%

with spring plowing as compared to the other tillage methods.

Corn root weight data are summarized in Table 7 from the Jackson site with Fairpoint minesoil and 7 in soil over spoil and from the Belmont site with Farmerstown minesoil with 46 in soil over the spoil, and reclaimed to Prime Farmland standards. Root weight in the 0-8 in depth was significantly higher at both sites compared to 8-16 in and 16-24 in depths. When tillage treatments are compared, only plant root data at the Belmont Farmerstown site differed significantly. Root weights from fall ripping were higher than from the lowest, spring plow, and vice versa, but neither differed significantly from the other two treatments.

Since only one of 13 site-years responded positively, these studies suggest that ripping to depth of 14-15 in has little benefit with these Ohio minesoils. Phase 4 studies demonstrate that spring plowing can cause adverse yield and plant development with minesoils if soil moisture stresses occur when seed is germinating.

CONCLUSIONS

Forty-one site-years corn production on Ohio reclaimed sites with primarily silt loam surface soil averaged 62% of natural soil comparison data and 80% of county average yields. Other evidences of stress on plants included 8% lower stands, 18.9 inch reduction in plant height, and 2% higher grain moisture at harvest. Increased depth of replaced topsoil-subsoil over spoil increased the opportunity for enhanced yields; but, apparent higher clay content in reconstructed profiles and compaction during reclamation severely limited corn production at some locations with deeper amounts of natural soil placed over the spoil. Farmerstown, Fairpoint, and Morristown had more conducive physical-chemical characteristics in the rooting zone for corn production than the Bethesda minesoil. Split applications of nitrogen increased its efficiency about 50% and was found necessary to insure season-long nutrition of this key plant nutrient. Chisel tillage to a depth of 14-15 in did not generally enhance yields or plant growth. Under drought stress, yields were depressed more on minesoils than on undisturbed natural soils. This research shows that neither adequate fertility nor chisel tillage to a depth of 14-15 in can restore the short-term productivity of corn on reclaimed land in SE Ohio compared to yields on comparable undisturbed soils.

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Table 7. Summary of corn root weight by depth and tillage treatments, Farmerstown Minesoil, Belmont County and Fairpoint Minesoil, Jackson County sites, Oct. 1986.

Depth of Soil	Farmerstown-Belmont Co.	Fairpoint-Jackson Co.
(inches)	(gm/sample)	(gm/sample)
0-8	1.463A	1.208A
8-16	0.174B	0.316B
16-24	0.045B	0.091B
$LSD_{(.05)}$	0.513	0.341
Tillage Treatment		
fall ripping	0.796A	
no-tillage	0.712AB	NS
sp plow	0.384AB	
sp plow	0.351B	
$LSD_{(.05)}$	0.418	
r^2	.92	.87
CV	70%	67%

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Rowcrop Response to High Traffic vs Low Traffic Soil Reconstruction Systems

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Abstract. Poor soil physical condition has been identified as the most limiting factor to successful row crop production on mined land in Illinois. Compacted mine soils lack a continuous macropore network to provide for water movement, aeration and root system extension. Critical to reclamation success are: i) selection of the best available soil materials used in soil construction, and ii) reclamation methods which will minimize compaction during soil reconstruction. Excellent corn and soybean yields have been acheived when reclamation methods result in low strength soils. Total crop failures have commonly occurred when high traffic soil replacement methods result in mine soils with high soil strength.

INTRODUCTION

This project centers around field experiments involving growing rowcrops on postmine soils. It is a continuation of reclamation research of mined land used for crop production that has been ongoing by the University of Illinois since 1977. In this paper we will look at two research sites which vary in method of reclamation and technique of mine soil construction. One site utilizes a high traffic scraper-haul system for soil replacement while the other utilize a uniques low traffic wheel-conveyor-spreader system which gently places soil material with minimal compaction. At each site there are two or more different kinds of postmine soils being rowcropped, some of these soils meet the requirements of both federal and state reclamation laws. Other soils vary from current regulations to allow testing the effects of a wide range of reclamation practices on soil productivity.

It is apparent that the material handling method used in soil construction affects the physical condition of the constructed mine soil. Where material is hauled and placed with rubber tired scrapers, the resultant mine soil is firm and massive or compacted throughout. Plant rooting in these soils tend to be shallow. Probability for reclamation success can be enhanced by utilizing techniques which eliminate or reduce wheel traffic during the soil construction process.

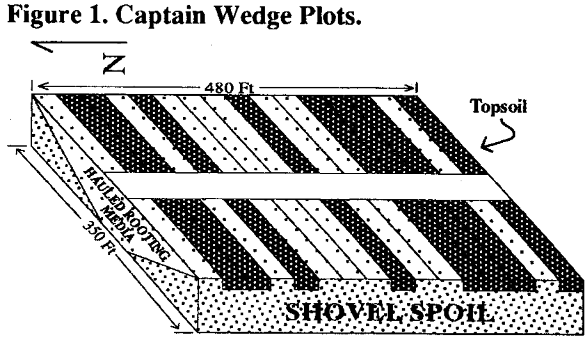
The objective of this research is to characterize and evaluate the effects of selected reclamation methods on soil productivity.

Site and Treatment Description

The Captain Mine, Arch of Illinois, Inc., is located in Perry County near Percy in southwestern Illinois. There are two experimental field plots which differ in design and objective. The first set of plots was constructed in 1978 and is a wedge design (Figure 1). It consists of shovel spoil (quite rocky) covered by a layer of scraper hauled root media (mostly B horizon material) varying in thickness from 0 to 4 feet. Superimposed are randomly located strips in eight replications that have had A horizon (topsoil) material replaced. Early yield results from this study are reported in a previous paper (Jansen et al., 1985). In addition to evaluating yield response to depth of rooting medium and topsoil replacement, a deep tillage treatment has been added as a treatment variable.

The second set of plots at Captain (Mix Plots) were designed to follow up a series of greenhouse experi-

Figure 1. Captain Wedge Plots.



ments which began in 1977. Greenhouse evaluation in that study revealed that replacement or alteration of the claypan subsoils of southern Illinois would increase crop growth by enhancing the chemical and physical properties of reclaimed land (Dancer and Jansen, 1981; McSweeney et al., 1981). Topsoil materials generally produced somewhat better plant growth than did the materials from soil B or C horizons, but mixtures of B and C horizons were commonly equal to or better than the B horizon materials alone. The purpose of these field plots was to evaluate several different available materials or soil mixtures for use in soil construction.

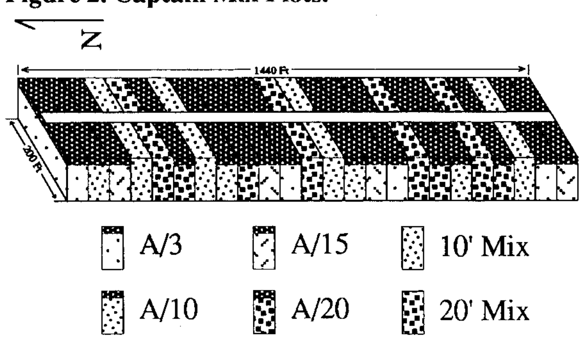
The mix plots, constructed in 1980, consist of a randomized complete block design with four replications (Figure 2) with the following treatments:

A/3	A and B horizon material from the premine soils replaced in their original sequence.
A/10	A horizon material segregated and replaced over a blend of the top 10 feet of premine soils and underlying substratum.
A/15	A horizon material replaced over a blend of the top 15 feet of premine materials.
A/20	A horizon material replaced over a blend of the top 20 feet of premine materials.
10' Mix	A blend of the top 10 feet of premine materials with no A horizon separation or replacement. The A horizon is a component of the root media blend.
20' Mix	A blend of the top 20 feet of premine materials with no A horizon separation or replacement.

The blending of varying increments of soil and unconsolidated material was achieved using a mining wheel. The soil material was transported by a conveyor belt and then placed with a soil spreader requiring minimal grading. Thus the term wheel-conveyor spreader system is used to describe this process.

Prime agricultural soils disturbed by surface mining for coal in this area primarily belong to the Stoy, Hosmer, and Cisne soil series. Stoy soils (fine-silty, mixed, mesic Aquic Hapludalf) are nearly level and

Figure 2. Captain Mix Plots.



gently sloping and are somewhat poorly drained. Hosmer soils (fine-silty, mixed, mesic Typic Fragiudalf) are gently sloping and sloping and are moderately well drained. Cisne soils (fine, montmorillonitic, mesic Mollic Albaqualf) are nearly level or depressional and are poorly drained. Soils of this region are formed on 4 to 6 feet of Peorian loess overlying Illinoian glacial till. Most of these soils have highly weathered acidic subsoils which are high in clay, highly plastic, and poorly aerated when wet. These subsoils tend to be only slowly permeable and, when dry, restrictive to root penetration. The C horizon consists of calcareous loess and calcareous glacial till and is chemically suitable for supporting plant growth.

Nearby tracts of Cisne silt loam and Stoy silt loam were used as unmined comparisons. Management factors for the mined and unmined soils are the same and similar to practices followed by a typical farming operation. Corn (*Zea mays* L.) and soybeans [*Glycine max* (L) Merr] are rotated each year within the experimental designs of the wedge and mix plots. Soybeans were not grown during the 1986 and 1987 seasons. A fallow period for each side with supplemental tillage to correct a tillage pan was applied during these seasons. Grain yield samples for corn were harvested after black-layer formation on the kernel indicated physiological maturity and soybeans were harvested when all pods were brown and dry. Grain yield estimates are based on the amount of shelled grain after adjusting for variation in moisture content of grain to 15.5% for corn and 12.5% for soybeans.

Objectives

1) Identify the best material for use in soil construction of the post mine soil.
2) Measure rowcrop growth and yield response to A horizon segregation and replacement.
3) Determine the relationship between rowcrop yields and thickness of selected rooting media material over graded shovel spoil.
4) Determine the rowcrop yield potential of reclaimed land, both annually and the trend over time.
5) Evaluate the relationship between rowcrop yields on reclaimed land and those on nearby undisturbed land.

RESULTS AND DISCUSSION

Captain Wedge

This experiment was designed to evaluate corn and soybean yield response to thickness of scraper placed rooting medium (0-48 in thick) over graded cast overburden , with and without topsoil replaced. Yields are presented in Tables 1 and 2. Results from the first six years (1979-84) show that yields of corn and soybeans increased with increasing root media depth to about the 25 in depth (Jansen et al., 1985). No significant yield increase was observed beyond this depth. This lack of response to increasing thickness beyond the 25 in depth might be caused by high soil strength due to compaction by scraper placement. Meyer (1983) found very few roots below the 25 in depth and also found that roots in the subsoil were largely confined to desiccation cracks. The subsoil condition can best be described as compact and massive with very high bulk density levels and poor water infiltration. These scraper built soils lack the macropore network needed to conduct water and to provide avenues for root growth. Thompson et al. (1987), measured penetrometer resistance readings of 280-540 psi on these plots and noted that plant roots were conspicuously absent below 26 inches in these high strength soils. McSweeney and Jansen (1984) reported that root penetration into these subsoils was confined primarily to the horizontal direction. Cross sections of roots were noticeably flattened and compressed in response to high soil strength.

Figure 3 presents the relationship of rooting media depth to long term mean yields of corn and soybeans. The regression models (logarithmic) of each crop show that over the 1979-90 period, yield response was closely associated to rooting media depth. The slope of the lines indicate the change in crop yield per unit change in rooting media depth. The slope is relatively flat, therefore there is only a small increase in yield with increasing root media depth. While a close relationship of yield and root media depth exists, yields are extremely low. Twelve year mean corn yields range from 25 bu/a at the three inch root media depth to 46 bu/a at the 44 inch depth. Similarly, mean soybean yields for a ten year period range from 7 bu/a to 11 bu/a. Observations of this study fall within a rather restricted range of values for the two variables of yield and rooting media depth. Even though there is a high coefficient of correlation, one should resist the temptation to extend the regression line beyond the range of observations (by extrapolation) to predict what would happen to yield if rooting media depth were to take on values above or below those actually observed. For example, using these regression

Table 1. 1979-90 corn yields on the Captain Wedge.

Depth	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
	Yield, bu/a											
Topsoil/Root Media:												
3"	81	0	37	63	0	0	0	0		16	0	
6"	69	0	37	46	0	0	0	0	105	9	0	
10"	77	0	40	65	0	0	0	0	114	9	0	
13"	45	0	39				1			15	0	
19"	90	0							120			
22"	89	0	51	84	0	0	19	22		27	19	
25"	89			72								
30"			51	59	0	0						
32"	89	0		51	0	0	24	14	139	21	10	21
37"	86	0	43				55†	30†	110†	32†	32†	28†
44"	92	0	50	50	0	0	47†	42†	138†	31†	36†	32†
Root Media Only:												
3"	60	0	31	80	0	0	0	0		18	0	
6"	68	2	39	60	0	0	0	0	69	19	0	
10"	61	0	52	78	0	0	0	0	84	24	0	
13"		1	58				12			29		
19"	77								106			
22"	82	5	68	100	0	0	26	24	123	45	4	
25"	94	0										
30"		1	60	71	0	0						
32"	81			67	0	0	28	15	97	36	7	25
37"	82	0	56				71†	37†	98†	46†	25†	44†
44"	78	5	73	60	0	0	56†	45†	130†	45†	40†	39†
Cisne	102	37	123	160	58				143	109	95	126
Stoy					0	67	31	149	33	25	56	
Target Yields:												
Base HCL[1/]	85	85	85	85	85	85	85	85	85	85	85	85
Adjusted					37	56	71	72	97	61	74	74

[1/] Base target yields of high capability lands (HCL) for Captain permit area calculated by IL Dept. of Agric. This base target yield is adjusted annually by a county success factor to adjust for weather variation.

† TLG Ripped

equations to calculate the amount of rooting media needed to achieve target level yields would require the replacement of 170 feet of rooting media for corn and 384 feet of rooting media for soybeans. It would be absurd to think that these depths would invoke a yield response.

Some relatively small portion of year to year rowcrop yield variation has been associated with root media thickness. A much greater portion of the total variation in yield among years has been associated with year to year weather effects, which have been enhanced by the droughty nature of these mine soils. Crops growing on these compacted soils are not able to take up enough water to survive and flourish during periods of even moderate drought stress.

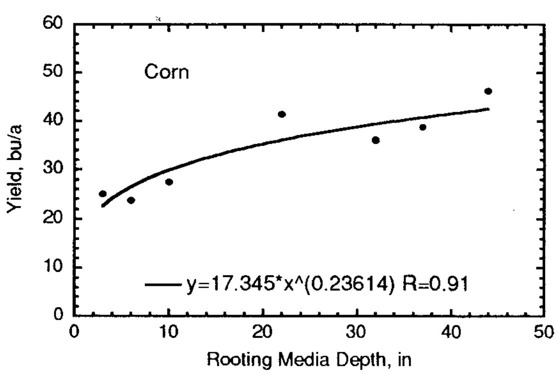
Little significant yield response to scraper placed topsoil replacement has occurred during the twelve years studied. While topsoil has been beneficial for seedbed preparation, stand establishment, and early season growth, it has not resulted in increased yields

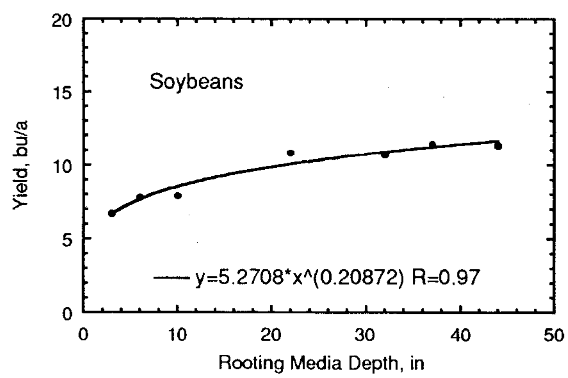
Table 2. 1979-90 soybean yields on the Captain Wedge.

Depth	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
	Yield, bu/a											
Topsoil/Root Media:												
3"	19	0	9	16	0	0	14	[2/]		0	0	0
6"	22	0	11	18	0	0	12			0	0	0
10"	23	0	12	16	0	0	12			0	0	0
13"		0	14	18	0	0						
19"	31						15					
22"	30	0	15	22	0	0	20			0		
30"		0	13	24	0	0						
32"	28	0					17			1	9	8
37"		0	18	25	0	0	27†					
44"	27	0	17	26	0	0	27†			3†	12†	11†
Root Media Only:												
3"	10	0	9	15	0	0	16			0	0	0
6"	12	0	12	18	0	0	19			0	0	0
10"	11	0	11	18	0	0	24			0	0	0
13"		0	14	20	0	0						
19"	14						25			0		
22"	16	0	18	23	0	0	29			0		
32"	13	0					22			1	9	7
37"		0	20	27	0	0	31†					
44"	12	0	19	26	0	0	24†			3†	13†	9†
Cisne	42	28	22	48	15					22	26	
Stoy					0	36			23		28	
Target Yields:												
Base HCL[1/]	28	28	28	28	28	28	28			28	28	28
Adjusted					14	18	25			21	17	23

[1/] Base target yields of high capability lands (HCL) for Captain permit area calculated by IL Dept. of Agric. This base target yield is adjusted annually by a county success factor to adjust for weather variation.
[2/] Soybeans were not grown in 1986 and 1987.
† TLG Ripped

Figure 3. Regression of 1979-90 mean yields to scraper placed root media depth on the Captain Wedge.





under these conditions. Yields of both crops have been extremely low, and total crop failures on these highly compacted mine soils have occurred in years of moderate to severe weather stress. Corn yields achieved on these plots were equal to the permit target yield in only one of the twelve years studied. Soybean yield response was similar. Plot yields were comparable to the target values in only one year of ten. It is probable that response to soil horizon replacement would have been greater had crop yield not been so severely limited by soil physical problems. In order to address this issue, a deep tillage treatment (Kaeble-Gmeinder TLG-12) was applied to the thick end of the wedge design. The TLG-12 vibratory deep ripper uses a cut-lift operation which, under favorable soil conditions, can shatter the soil to a depth of 32-33 in. 1985-90 yield results of this tillage treatment is presented in Table 3.

Corn yields were significantly higher for the TLG treatment in four of the six years and in one year for soybeans. Yields for the TLG treatment were still well below calculated target yields in most years. Very good corn yields were obtained on both the TLG and No TLG treatment in 1987. Weather in that year was characterized as having considerably above normal rainfall with little or no weather stress throughout the growing season. This data suggests that even though significant responses have occurred, a deeper tillage treatment is necessary to achieve productivity levels on these highly compacted scraper placed soils.

Captain Mix

Excellent corn and soybeans yields have resulted on these low strength soils in high stress as well as low stress years. Rowcrop yields comparable to those obtained on nearby undisturbed soils have been achieved in all ten years of this study (Table 4). This is due to the excellent physical properties obtained through this soil handling and minimal grading soil reconstruction process. These wheel-conveyor spreader mixture plots have subsoils consisting of pockets of compacted material within a framework of loosely compressed aggregates of varying sizes. McSweeney and Jansen (1984) described this condition as a "fritted" soil structure in these replaced soil materials. Fritted structure has been defined as an artificial soil structure consisting of rounded loose aggregates formed by rolling along a soil conveyor. This structure gives the soil a low strength and a high content of macropores. The extensive void spaces between aggregates allow for excellent root penetration. Roots are diffusely distributed to depths of 60 in or more in these mine soils. Crops growing on these soils persist through much more severe drought periods than on severely compacted soils (McSweeney et al. 1987).

Penetrometer data taken in May 1989 (Table 5) reflect the excellent physical condition resulting from replacement of rooting materials with the wheel-conveyor spreader system. Significant differences in mean treatment penetrometer values exist between treatments, however, the magnitude of soil strength levels are quite low compared to the scraper hauled system. Results indicate that topsoil grading had an effect on the 9-18 in depth segment. Topsoil replaced treatment soil strength readings were significantly higher than the non-topsoiled plots at this depth.

Topsoil, replaced with the soil spreader and graded by dozer, has only infrequently produced any significant yield response. Both topsoil and non-topsoil treatments have been able to produce corn and soybean yields comparable to those obtained on the undisturbed tracts (Figure 4).

SUMMARY

Results from the Captain Mine experiments demonstrate that poor physical condition is the most limiting factor in the reclamation of farmland soils. Segregation and replacement of horizons from premine soils is a practice that is required by law, and we should strive

Table 3. Yield response to the TLG deep tillage on the Captain Wedge.

Tillage Trt	1985	1986	1987	1988	1989	1990	1991	Mean
	Yield, bu/a							
	Corn							
TLG1	57 a	40 a	119 a	39 a	33 a	36 a	19	49 a
No TLG	24 b	19 b	123 a	32 a	10 b	23 b	10	34 b
Target Yield-HCL	85	85	85	85	85	85	85	
Adjusted	90	92	97	61	94	75		
	Soybeans							
TLG	27 a			3	12 a	10 a	0	10
No TLG	21 b			1	9 a	8 a	0	8
Target Yield-HCL	28			28	28	28	28	
Adjusted	25			21	17	23		

[1/]TLG refers to Kaeble-Gmeinder TLG-12 deep ripper which has an effective tillage depth of 32-33 inches.

Table 4. 1981-91 corn and soybean yields on the Captain Mix experiment.

Soil Trt	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	Mean
						Yield, bu/a						
						Corn						
A/3[1/]	113 a[2/]	144 abc	72 a	125 a	109 ab	111 a	152 cd	79 c	123 a	113 a	102 a	113
A/10	83 c	152 ab	52 ab	113 ab	93 c	115 a	167 ab	89 bc	127 a	115 a	103 a	109
A/15	105 ab	121 d	69 ab	115 a	110 a	109 a	163 bc	86 c	133 a	126 a	99 a	111
A/20	92 bc	130 cd	53 ab	108 ab	96 bc	99 a	177 a	85 c	119 a	129 a	96 a	98
10' Mix	56 d	145 ab	47 ab	98 b	76 d	69 b	152 cd	90 bc	121 a	123 a	116 a	100
20' Mix	81 c	140 bc	40 b	99 b	81 cd	107 a	146 d	100 ab	155 ab	122 a	96 a	102
Cisne	123 a	160 a	58 ab				143 d	109 a	95 b	126 a	118 a	
Stoy				0	67 d	31 c	149 cd	33 d	25 c	56 b	38 b	
Target Yields:[3/]												
Base Prime	119	119	119	119	119	119	119	119	119	119	119	
Adjusted			51		99	101	136	85	104	105		
Base HCL	85	85	85	85	85	85	85	85	85	85	85	
Adjusted			37	56	71	72	97	61	74	75		
						Soybeans						
A/3	35 a[2/]	49 a	18 a	31 ab	45 a	[4/]		23 a	27 a	27 a	14 a	29
A/10	29 bc	38 b	14 ab	31 ab	43 a			25 a	24 b	31 a	11 a	27
A/15	26 c	40 b	15 ab	32 a	43 a			23 a	26 a	31 a	13 a	27
A/20	27 bc	41 b	13 ab	32 a	40 ab			23 a	23 b	31 a	13 a	27
10' Mix	25 c	39 b	11 b	27 ab	36 b			21 a	22 b	25 a	16 a	24
20' Mix	31 b	43 ab	12 ab	27 b	35 b			21 a	19 c	27 a	10 a	25
Cisne	22 c	48 a	15 ab					22 a	26 a		16 a	
Stoy				0	36 b			23 a		29 a	10 a	
Target Yields:[3/]												
Base Prime	36	36	36	36	36			36	36	36	36	
Adjusted			18		32			27	27	30		
Base HCL	28	28	28	28	28			28	28	28	28	
Adjusted			14	18	25			21	17	23		

[1/] Soil treatments are: A/3, topsoil replaced over a mixture of the top 3 ft of original soil; A/10, topsoil replaced over a mixture of the top 10 ft; A/15, topsoil replaced over a mixture of the top 15 ft; A/20, topsoil replaced over a mixture of the top 20 ft; 10' Mix, a mixture of the top 10 ft of original soil, including topsoil; 20' Mix, a mixture of the top 20 ft of original soil, including topsoil.

[2/] Values followed by the same letter within a crop and year are not significantly different at the 0.05 level.

[3/] Base target yields of prime lands and high capability lands (HCL) for Captain permit area calculated by IL Dept. of Agric. This base target yield is adjusted annually by a county success factor to adjust for weather variation.

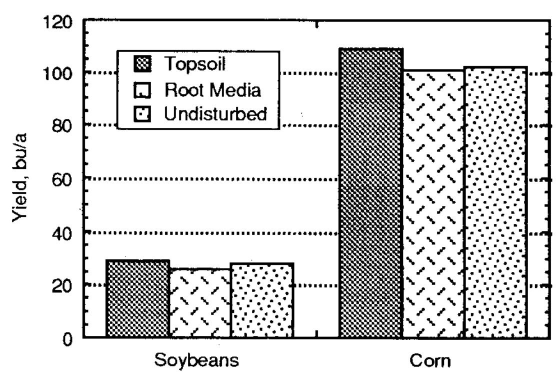
[4/] Soybeans were not grown in 1986 and 1987.

Table 5. Mean penetrometer resistance values for soil treatments on the Captain Mix plots.

Treatment	Depth 9-18"	18-27"	27-36"	36-44"
	Penetrometer Resistance, PSI			
A/3[1/]	178.7 abc	97.4 d	76.7 b	97.9 b
A/10	183.1 ab	135.5 bc	91.4 b	96.2 b
A/15	209.6 a	161.2 ab	124.6 a	111.3 ab
A/20	219.2 a	175.6 a	117.4 a	108.3 ab
10' Mix	134.6 c	102.5 b	100.2 ab	170.1 a
20' Mix	121.4 c	110.0 cd	100.9 ab	111.5 ab
LSD (0.05)	57.6	30.3	37.5	61.9

[1/] Values followed by the same letter within a depth segment are not significantly different at the 0.05 level. Soil treatments are: A/3, topsoil replaced over a mixture of the top 3 ft of original soil; A/10, topsoil replaced over a mixture of the top 10 ft; A/15, topsoil replaced over a mixture of the top 15 ft; A/20, topsoil replaced over a mixture of the top 20 ft; 10' Mix, a mixture of the top 10 ft of original soil, including topsoil; 20' Mix, a mixture of the top 20 ft of original soil, including topsoil.

Figure 4. 1981-1991 mean crop yields for undisturbed soil, topsoil and root media treatments on Captain Mix plots.



to select the best possible rooting materials for reclamation, but desirable physical properties are essential to attaining productivity levels necessary for bond release. Productivity success of this concept becomes quite evident when comparing the A/3 treatment on the wheel-conveyor mixture plots and the topsoil/scraper root media from the wedge plots. These soils were constructed with essentially the same soil materials; A horizon overlying B horizon. But the A/3 mix treatment has produced significantly higher corn and soybean yields than yields of the scraper placed rooting media wedge in every year studied. The major difference between the two mine soils is the method of soil replacement and resulting level of soil compaction. Soil tests (Table 6) indicate that soil fertility is neither a limiting factor nor the major influence in the yield differences of these soils.

Although the mining wheel-conveyor spreader system has proven successful in constructing productive soils after surface mining, it does not offer a generally applicable solution to the problem of restoring land to agricultural productivity after mining. It is a very inflexible system which can not be used at most mine sites. Evident options are to either develop a method by which excessively compacted soils can be ameliorated to a significant depth or to develop other material handling options which will produce soils with good physical characteristics and will be more cost competitive and applicable than the conveyor system. Natural soil improvement processes are slow, especially at greater depths, as is evident from the 10 year corn and soybean yield trends from the wedge and mix plots (Figure 5). Year to year and across years variation is associated more with weather stress and management factors than from any measurable natural soil improvement.

ACKNOWLEDGEMENTS

This work was supported by funds from Amax Coal Co., Arch of Illinois, Inc., Consolidation Coal Co., Cooperative States Research Service (USDA), Freeman United Coal Co., Illinois Agricultural Association, Illinois Agricultural Experiment Station, and Peabody Coal Co.

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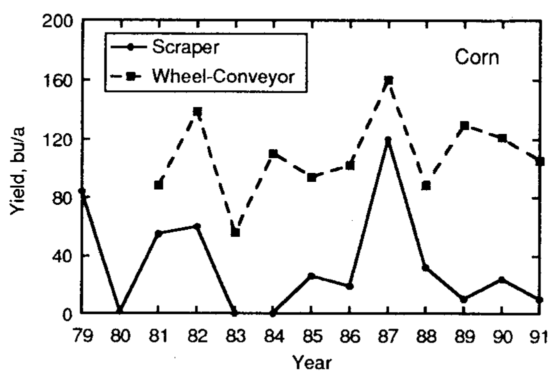
Figure 5. Mean 1979-91 corn and soybean yields across the scraper placed root media wedge and the wheel-conveyor-spreader mix treatments at Captain mine.



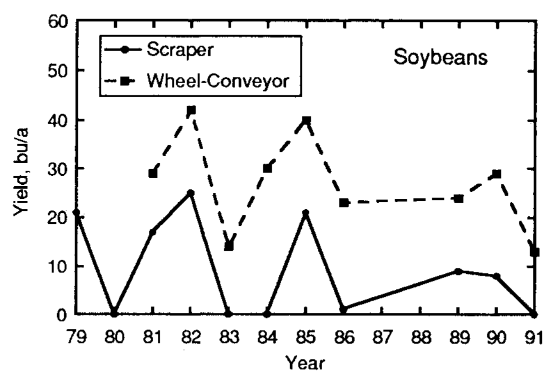


Table 6. 1991 soil test means for soil treatments (A horizon overlying B horizon) for Captain Mix and Captain Wedge.

Trt	Depth	pH	CEC	P	Ca	Mg	K	Na	S	B	Fe	Mn	Cu	Zn
				- - - - - - - - - lbs/acre - - - - - - - - -					- - - - - - - - Parts per Million - - - - - - - -					
A/3[1/]	0-8"	6.5	12.4	71	3168	481	293	107	21	.363	171	80	1.2	0.97
TS/RM	0-8"	6.7	13.3	98	3682	523	360	140	36	.465	193	122	1.6	1.40
A/3	8-16"	7.3	16.2	32	3764	1002	109	695	28	.408	150	94	2.1	1.18
TS/RM	8-16"	6.3	20.9	45	4597	1165	144	350	122	.401	163	112	1.8	1.65

[1/] Treatments are as follows: A/3, topsoil replaced over a mixture of the 3 ft of original soil using the wheel-conveyor spreader method; TS/RM, topsoil replaced over B horizon material using the scraper haul system.

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Rowcrop Response to Truck and Scraper Hauled Root Media Systems in Soil Reconstruction

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Abstract. Corn and soybean response to mine soil construction with end-dump trucks and scrapers was studied from 1985-1991 in southern Illinois. Two truck-hauled treatments, one which limited truck traffic to the spoil base only, and one which allowed truck traffic on the rooting media as it was placed, were evaluated. A third treatment was constructed with scraper-hauled rooting media. Trucks were shovel loaded with subsoil materials of the natural unmined soil near the borrow area where the scrapers loaded. All treatments had 8 in of topsoil replaced over the rooting media. Significant differences in soil strength, a measure of soil compaction, and rowcrop yields were observed among treatments over the seven year period. The lowest soil strength and the highest row crop yields occurred on the truck-without-traffic treatment. Soil strengths and yields were similar on the truck with surface traffic and the scraper treatments

INTRODUCTION

The physical condition of reconstructed soils has been identified as a major factor affecting crop performance (Jansen, et al., 1985). Low yields, limited rooting, and drought susceptibility result from highly compacted soils. Deep tillage is becoming an accepted practice to improve the physical condition of these soils, and the effects of tillage depth and timing are currently being studied (Dunker, et al., 1990). Acceptable yields can be achieved on soils with a more favorable, less compacted subsoil (Dunker, et al., 1991). The degree of compaction, type of structure, and soil strength is a result of the material handling methods used during reconstruction. Methods of handling rooting media which minimize compaction and provide a more favorable structure could reduce the amount of augmentation (deep tillage), if any, required to restore productivity.

The two basic methods included in this study are the scraper and the shovel-truck haulback systems. They are very different in the methods of excavation and placement. The scraper excavates in successive layers from a borrow area, once the topsoil is removed. Successive loads may be from the upper B horizon and on down through the parent material as long as texture meets requirements. Excavation is accomplished by shearing the layers out with a large blade on the front of the scraper pan. These layers may vary in thickness from 6-12 inches or more, depending on conditions of the borrow area. The material is sheared out, and by force folded and crumbled into the pan. Large blocks of naturally compacted till may remain with minimal disturbance. The placement is also in layers with compaction from wheel traffic buried throughout the profile.

The shovel generally excavates from a 10-20 foot highwall. The soil is mixed as the bucket loads from the bottom to the top of the highwall. The teeth on the bucket shear and fracture the material into small peds. At this point, the material is similar to that produced by a wheel excavator. Methods of truck hauling and placement vary with bottom and end dumps being used. The soil is generally deposited in a single layer with surface traffic from the trucks and grading being the only sources of compaction prior to topsoil placement.

OBJECTIVES

1) Evaluate the effect of shovel-truck and scraper rooting media replacement methods on rowcrop performance and soil physical properties.
2) Determine rowcrop yield potential of reclaimed land, both annually and longterm.
3) Determine the relationship between crop yields on reclaimed land and those on nearby undisturbed land.

MATERIALS AND METHODS

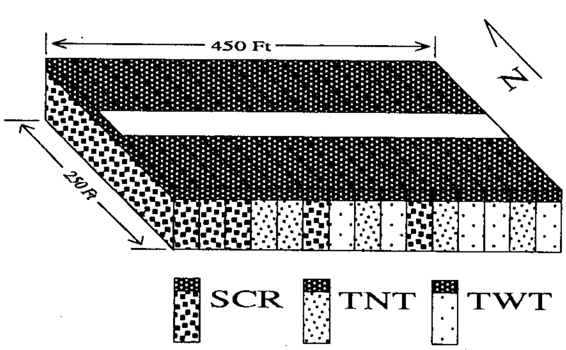
Site and Treatment Description

The Denmark Mine, Arch of Illinois, Inc., is located in Perry County near Willisville in southwestern Illinois. It is adjacent and immediately south of the Captain mine. Experimental plots at this site were established to evaluate a material handling system as an alternative to scrapers in mine soil reconstruction. End-dump trucks were in use at the mine site and were selected for two treatments to be compared with the scraper. One truck treatment has traffic induced on the surface of the rooting media. It is similar to the method used by the mine where trucks unload from the surface of the rooting media. In the other truck treatment, unloading was done from the base level (graded shovel spoil) and traffic on the surface was limited to grading with dozers. The construction of these plots was completed in July of 1984. The first cropping year was 1985. The experimental design (Figure 1) consisted of completely randomized design with five replications of three material handling treatments:

- SCR Topsoil replaced over scraper-hauled rooting media.
- TNT Topsoil replaced over truck-hauled rooting media without surface traffic on root media. In this treatment, the trucks were driven on the base (shovel spoil) material.
- TWT Topsoil replaced over truck hauled rooting media in which the truck traffic was on the root media.

During construction, the base material (spoil) was graded and the scraper plots were completed. Truck-hauled rooting material composed of a mixture of B and C horizon material was shovel loaded from a highwall near the scraper borrow area and placed from the base level. The plots selected for surface traffic were compacted as uniformly as possible using an empty DJB rear-dump truck. The soil moisture was quite high and a heavier load could not be supported. With these conditions, the truck induced residual compression/ plastic deformation to the surface of the rooting media. Ridges from the tire tracks were leveled to provide a more uniform topsoil depth. Scraper -hauled rooting media was direct hauled from scraper borrow area adjacent to truck material source. Topsoil was lifted from the high-wall side from a field just north of the plot area. Windrows were built on the north and center turnstrips of the plots. Topsoil was then pushed out and leveled with dozers. This method was chosen to minimize the effect of compaction of the rooting media from topsoil placement.

Figure 1. Denmark Plots.



Prime agricultural soils disturbed by surface mining for coal in this area primarily belong to the Stoy, Hosmer, and Cisne soil series. Stoy soils (fine-silty, mixed, mesic Aquic Hapludalf) are nearly level and gently sloping and are somewhat poorly drained. Hosmer soils (fine-silty, mixed, mesic Typic Fragiudalf) are gently sloping and sloping and are moderately well drained. Cisne soils (fine, montmorillonitic, mesic Mollic Albaqualf) are nearly level or depressional and are poorly drained. Soils of this region are formed on 4 to 6 feet of Peorian loess overlying Illinoian glacial till. Most of these soils have highly weathered acidic subsoils which are high in clay, highly plastic, and poorly aerated when wet. These subsoils tend to be only slowly permeable and, when dry, restrictive to root penetration. The C horizon consists of calcareous loess and calcareous glacial till and is chemically suitable for supporting plant growth.

Nearby tracts of Cisne silt loam and Stoy silt loam were used as unmined comparisons for this experiment. Management practices for the mined and unmined soils are the same and follow those recommended for high level crop production. Corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.] are rotated each year within the experimental designs. Grain yield samples for corn are harvested after black-layer formation on the kernel has indicated physiological maturity and soybeans are harvested when all pods are brown and dry. Grain yield estimates are based on the amount of shelled grain after adjusting for variation in moisture content of grain to 15.5 % for corn and 12.5 % for soybeans.

RESULTS AND DISCUSSION

The constant-rate cone penetrometer (Hooks and Jansen, 1986) was used in April, 1987 to record soil strength measurements of the different soil replacement methods (Table 1). Soil strength levels of the scraper-hauled treatment (SCR) were significantly higher than the truck-without-traffic treatment (TNT) for all four segment depths. The truck-with-traffic treatment (TWT) was numerically lower than the SCR treatment and numerically higher than the TNT treatment but was not significantly different from either at the 0.05 level of significance. In summary, soil strength values decreased with decreasing traffic.

Soil pit excavations revealed a massive subsoil structure in the scraper treatments with corn roots limited to flattened mats in desiccation cracks. Some of these cracks are formed at an interface between blocks of soil that were pressed together during the scraper placement. The subsoil structure in the TNT treatment was similar to the fritted structure described by McSweeney (McSweeney and Jansen, 1984) with roots being able to exploit the rooting zone completely.

Differences in crop performance were observed between treatments during this study. Corn plants grown on the TNT plots, in all years, were noticeably taller with heavier stalks than those grown on the SCR plots. The TWT plots produced plants similar to the TNT plots in years with favorable weather. In years with more drought stress, plants on the TWT plots were not as vigorous as those on the TNT plots, but noticeably superior to those on the SCR plots. Symptoms of drought/heat stress would appear first on the SCR plots. If drought conditions continued, leaves would also curl on the TWT and TNT plots. Upper leaf necrosis was common on the SCR plots. During these dry periods, the plants on the TNT plots would remain dark green in color while nearby plants on the SCR plots would change to a pale gray-green with severe leaf necrosis. The differences in soybeans were less dramatic with the TNT plots usually producing taller plants with more pods than the other two treatments. Observations have been recorded from the ground as well as with color and infrared aerial photography.

Table 1. Mean penetrometer resistance values for soil treatments at the Denmark Mine.

Treatment	9-18"	18-27"	27-36"	36-44"
	---------- Depth ----------			
	Penetrometer Resistance, PSI			
TNT[1/]	182.0 b[2/]	188.5 b	161.3 b	172.3 b
TWT	223.2 ab	226.9 ab	213.0 ab	216.7 ab
SCR	271.7 a	274.1 a	257.8 a	258.1 a
LSD (0.05)	70.2	60.1	53.7	47.7

[1/] Treatments are: TNT, truck-placed rooting media with no traffic allowed on root media surface; TWT, truck-placed rooting media with the truck traffic directly on root media surface; SCR, scraper-placed rooting media.

[2/] Values followed by the same letter within a depth are not significantly different at the 0.05 level.

Soybean yields were affected by insect pressures (mostly grasshoppers) in years with dry periods in late July and August. The research site is located near a large area of grass pasture which turns dormant during these periods, which causes a mass migration of insects which is difficult to control.

1985 to 1991 corn and soybean yield responses show similar trends to soil strength data. The truck-without-traffic treatment (TNT) has produced the highest corn yields of any of the mine soil treatments in every year of the study (Table 2). These yields have also been comparable to the corn yields produced on the undis-

Table 2. 1985-90 corn and soybean yields at Denmark Mine.

Soil Trt	1985	1986	1987	1988	1989	1990	1991	Mean
	------------ Yield, bu/a ------------							
	Corn							
TNT[1/]	98 ab	64 a	146 a	91 a	93 a	113 a	92 ab	99
TWT	85 bc	48 ab	110 b	56 b	58 b	82 b	70 bc	71
SCR	74 c	37 b	116 b	45 bc	47 b	77 bc	48 cd	63
Cisne			143 a	109 a	95 a	126 a	118 a	
Stoy	115 a	31 b	149 a	33 c	25 c	56 c	38 d	
Target Yield-HCL[2/]	89	89	89	89	89	89		
Adjusted Target	74	76	102	64	78	78		
	Soybeans							
TNT	29 b	23 ab	36 a	2 b	24 a	24 a	5 c	20
TWT	24 b	18 bc	30 bc	2 b	16 b	15 b	2 c	16
SCR	26 b	16 c	27 c	3 b	12 b	14 b	3 c	14
Cisne			36 ab	22 a	26 a		16 a	
Stoy	36 a	28 a	32 abc	23 a		29 a	10 b	
Target Yield-HCL[2/]	29	29	29	29	29	29	29	
Adjusted Target	26	29	29	22	21	24		

[1/] Values followed by the same letter within a crop and year are not significantly different at the 0.05 level.

[2/] Base target yields of high capability lands (HCL) for Denmark permit area calculated by IL Dep of Agric. This base target yield is adjusted annually by a county success factor to adjust for weather variation.

turbed soils in every year. Corn yields of the truck-with-traffic (TWT) and the scraper treatment (SCR) have not been significantly different in any year. Soybean yield response has been somewhat more variable but similar trends have occurred. TNT soybean yields were comparable to the undisturbed soils in four of the six years. TWT and SCR treatment soybean yields were not significantly different in all seven years.

Corn from the TNT treatment had significantly higher test weight, ear weight, and shelling percentage (Table 3). The TNT treatment also produced a significantly lower percentage of barren plants. Percentage barren plants, shelling percentage, and ear weight were similar for the TWT and SCR treatments. Corn from the TWT treatment had a significantly higher test weight than that from the SCR treatment but lower than corn from the TNT treatment. These variables from the TNT treatment were similar to those from the unmined Cisne soil and superior to those from the unmined Stoy soil.

The soil tests (Table 4) indicate a high level of fertility management. The levels of major and minor elements are adequate and should not be limiting to yields across treatments.

Net water extracted by the growing crop has been highest for the truck without traffic (TNT) treatment and the lowest for the scraper treatment (Figure 2). There is no reason to expect significant differences among these treatments in surface infiltration because all three treatments were topsoiled in the same way. The higher net extraction is an affect of the rooting media and likely indicates that more total water was available to and used by the growing crop. The yield data supports that conclusion; the TNT treatment produced significantly higher yields. Earlier research at this site, reported significantly lower root length densities for the scraper treatment (SCR) at the 18-24 in and 28-33 in depths compared to the truck-hauled treatments (R. H. Teyker, personal communication).

Figure 2. Mean water extraction from Jun-Aug for soil replacement methods.

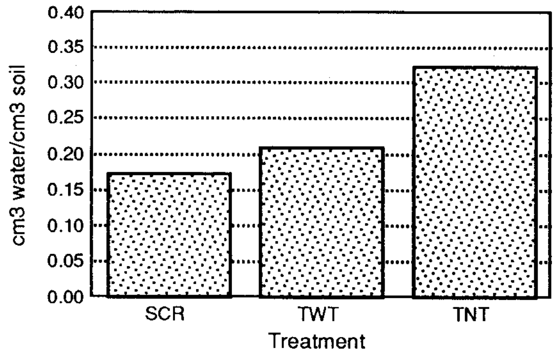


Table 3. 1985-91 mean values for measured corn yield variables.

Soil treatment	% Barren Plants	Shelling %	Ave. Ear Wt	Test Wt
		1987-91 Mean		
CIS[1/]	4.9 c[2/]	82.5 a	.408 a	57.3 a
STY	21.6 a	77.0 d	.249 d	55.9 bc
TNT	7.2 c	82.2 ab	.364 b	56.9 a
TWT	13.8 b	78.6 cd	.282 c	56.1 b
SCR	15.3 b	79.7 bc	.254 cd	55.4 c

[1/] Soil treatments are: CIS, undisturbed Cisne soil; SCR, scraper-placed root media; STY, undisturbed Stoy soil; TNT, truck-placed rooting media with no traffic on the root media; TWT, truck-placed rooting media with the truck traffic directly on the root media.

[2/] Values followed by the same letter within a variable are not significantly different at the 0.05 level.

Table 4. Soil test means for soil treatments at the Denmark Truck Experiment, 1990.

Treatments Soil	Depth	pH	CEC	P	Ca	Mg	K	Na	S	B	Fe	Mn	Cu	Zn
				lbs/acre					Parts per Million					
CIS[1/]	0-8"	6.3	9.5	50	2678	202	266	29	12	.306	145	95	1.04	1.22
STY	0-8"	6.6	9.2	47	2633	296	206	22	10	.340	96	119	0.91	1.16
TNT	0-8"	5.7	19.0	90	3547	913	394	82	43	.346	161	117	1.09	1.28
TWT	0-8"	5.9	18.3	82	3451	988	350	98	44	.374	150	126	1.04	1.22
SCR	0-8"	6.7	16.7	87	4025	976	387	74	48	.428	138	117	1.43	1.48
CIS	8-16"	5.7	8.7	18	1994	246	60	66	18	.335	111	39	0.46	0.95
STY	8-16"	5.6	10.7	20	2051	433	76	30	27	.398	129	54	0.48	0.85
TNT	8-16"	6.5	16.0	22	3082	1312	101	269	77	.276	122	87	0.91	0.94
TWT	8-16"	6.1	18.6	25	3314	1372	128	328	81	.272	127	77	1.06	1.06
SCR	8-16"	7.3	19.3	15	5000	1332	127	154	163	.486	109	176	0.91	1.24

[1/] Soil treatments are: CIS, undisturbed Cisne soil; SCR, scraper-placed root media; STY, undisturbed Stoy soil; TNT, truck-placed rooting media with no traffic on the root media; TWT, truck-placed rooting media with the truck traffic directly on the root media.

SUMMARY AND CONCLUSIONS

The weather patterns over the seven years of this study have provided a good test in a relatively short time period. Rainfall has ranged from excessive to severe drought. Over this range of weather patterns, the trends across treatments have remained the same.

The shovel-truck system that includes truck placement from the base level can produce a more productive soil than the scraper system. Yields from this shovel-truck system indicate restoration of productivity when compared to the unmined sites over the seven year period of this study. Traffic on the surface of the rooting media which has been shovel loaded and carefully placed can significantly reduce productivity. In this case, some level of augmentation may be required to improve the physical condition of the soil. Traffic patterns should be controlled to minimize unnecessary compaction when using end-dump trucks. Yields from the scraper system have fallen well short of acceptable levels during this study. A thorough augmentation of the physical condition of the soil profile may be required to restore productivity.

ACKNOWLEDGMENTS

This work was supported by funds from Amax Coal Co., Arch of Illinois, Inc., Consolidation Coal Co., Cooperative States Research Service (USDA), Freeman United Coal Co., Illinois Agricultural Association, Illinois Agricultural Experiment Station, and Peabody Coal Co.

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Reclamation of Alluvial Valley Soils in Texas Using Mixed Overburden

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Abstract. Studies on the feasibility of using mixed overburden as a revegetation medium have been conducted in alluvial floodplains of the Brazos and Trinity rivers in Texas where land is underlain by lignite. Yield of crops and survival of trees were significantly higher on the mixed overburden compared to native soils. The higher crop yields and tree survival were largely due to improved physical properties of the soils due to mixing.

INTRODUCTION

Surface mining and reclamation operations in alluvial soils must be conducted in a manner which insures that the agricultural utility and level of productivity in the affected areas are reestablished (Railroad Commission of Texas, 1983). In addition, the important characteristics supporting the essential hydrologic functions of the floodplain must be preserved during and after mining. Revegetation success is measured on the basic of a comparison of actual crop production from the disturbed area compared to reference areas or to a predetermined target level of crop production approval by the Commission. In accordance with the current philosophy of the state regulators, revegetation on prime farmland is considered a success when the adjusted 3-year average annual crop production is equal to or higher than the predetermined target level of crop production in the mining permit.

Numerous studies have been conducted regarding reclamation of mine soils. Kohnke (1950) discussed the reclamation aspects of spoil from surface mining and described the changes in soil physical conditions as they affect plant growth and subsequent land use. Minesoils can be constructed with variable chemical and physical properties by amending the original soil with suitable materials from below the surface horizon (Dancer and Jansen, 1981; Dunker et al., 1982; Hargis and Redente, 1984). Topsoil materials have generally produced better plant growth but materials from the B and C horizons have provided adequate revegetation substrate in some instances (Dancer and Jansen, 1981; McSweeney et al., 1981; Stucky and Lindsay, 1982). Reduction in yield is commonly due to compaction by equipment with the resulting high bulk densities and reduced rooting volume for the crop (McSweeney et al., 1987; McSweeney and Jansen, 1984). Hons et al. (1978) have outlined the problems associated with revegetation of leveled surface mined lands in Texas.

Much of the mining for lignite in Texas has been conducted on upland topographical positions on deep, sandy soils or clay pan soils with thin sandy surface horizons (Hossner et al., 1982). Mining for lignite in alluvial floodplain systems could result in inferior crop productivity of reclaimed soils if the overburden is not properly handled. The choice to be made is whether the topsoils should be stored and replaced or whether the productivity of the soils can be maintained or enhanced by mixing. Replacement of topsoil on clayey sites commonly results in pan formation, reduced root growth, and decreased productivity relative to native soils, particularly in dry years.

Lignite recoverable by surface mixing is located in alluvial floodplain systems in Texas. Two of the major alluvial systems where lignite could be mined are the Brazos and Trinity rivers. The primary agricultural crops in the Brazos river are cotton, corn, and grain sorghum. Trinity river alluvial soils are used for row crops, trees, and pasture. The results of two studies are reported here where crops were established on alluvial materials which were randomly mixed for revegetation without salvaging topsoil.

The objective of these studies was to determine the influence of deep overburden mixing on the chemical and physical properties of leveled alluvium and to measure productivity of several crops on the leveled alluvium relative to the productivity of a similarly managed native soil.

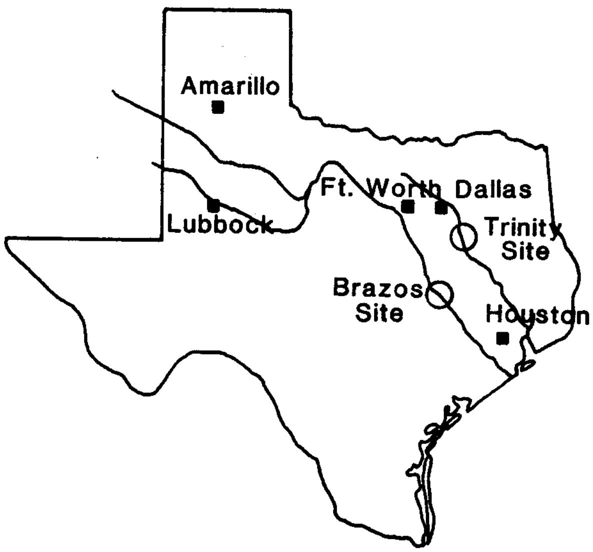
METHODS

Soil surfaces at each location (Figure 1) were prepared by excavation and mixing followed by replacement of the excavated soil, leveling, and planting of the test crop. Fertilizer was applied according to crop needs at the Trinity location and at variable rates at the Brazos location. A summary of selected site practices is given in Table 1.

Vegetative species were selected based on the current land use and the probability for successful planting and survival of selected tree species.

Cotton (Gossypium hirsutum) and grain sorghum (Sorghum bicolor) were the test crops at the Brazos location. Treatments were replicated 4 times. Coastal bermudagrass (Cynodon dactylon (L.) Pers) is the most widely planted perennial grass in the region and was selected as the primary species for evaluation on the Kaufman clay at the Trinity site. Green ash (Fraxinus pennsylvanica, lanceolata), autumn olive (Elaeagnus umbelleta), pecan (Carya illinoensis), and water oak (Quercus nigra) were also evaluated at the Trinity site. Treatments were replicated 3 times.

Figure 1. Locations of Brazos and Trinity River Alluvial Floodplain Sites.



Soils were analyzed at various stages in the experiments. Laboratory procedures followed those commonly used for evaluation of soil and overburden. Soil pH (Peech, 1965) and electrical conductivity (Bower and Wilcox, 1965) were determined on a 1:1 soil: water slurry. Texture (Sobek, et al., 1978), organic carbon (Nelson and Sommers, 1982) and exchangeable cations (Thomas, 1982) were determined on representative samples.

Forages and row crops were harvested from known plot areas and converted to forage, grain, or lint yields per acre. Survival and growth parameters (height and stem diameter) were determined in tree plots at the Trinity river site.

RESULTS

Soil

The Roetex soils (fine, mixed, thermic, Udertic Haplustoll) of the Brazos River floodplain are formed in fine textured alluvium along streams carrying sediments from Permian red beds. The soil ranges from mildly alkaline through moderately alkaline. Depth to soft powder calcium carbonate is 30 inches or more, but the soil is typically calcareous to the surface. Shallow and deep mixing increased soil pH, clay content and

Table 1. Treatments and cultural practices at field site locations.

Soil	Location	Mixing Treatments	Crops	Applied Fertilizer N	P_2O_5	K_2O
				lbs A^{-1}		
Roetex clay (fine, mixed, thermic, Udertic Haplustoll)	Brazos River, Robertson County	1) Control 2) top 2' mixed, replaced 3) top 10' mixed, replaced	1) cotton 2) grain sorghum	1) 0,40,80,160 2) 0,40,80,120, 240	1) 0,40	1) 50
Kaufman clay (very fine, mont-morillonitic thermic, Typic Pelludert)	Trinity River, Henderson County	1) Control 2) top 20' mixed, replaced	1) Forage grass 2) trees	1) Based on soil test recommendation		

exchangeable Ca and Mg (Table 2) compared to the original Roetex soil.

The Kaufman clay soils of the Trinity river floodplain (very fine, montmorillonitic, thermic Typic Pelluderts) are medium acid in the surface and calcareous at depths of 24 inches or greater. The Kaufman soils are extensive and located on level to gently sloping flood plains of streams draining the Blackland Prairies. Deep mixing of the soil resulted in free calcium carbonate coming to the surface, an increase in soil pH to 8.1, and a dramatic decrease in clay content of the surface soil (Table 2).

Productivity

Brazos River Alluvial Site

Three years of data for cotton yields and 2 years of grain sorghum yields were collected at the Brazos River site. The influence of N, P, and K fertilizer application was incorporated into this experiment.

The trend for both crops was increasing yields with increasing rate of N application to 40 lbs N A^{-1} There was a significant increase in cotton lint yield to 40 lbs P_2O_5 A^{-1} in the first year following disturbance but not in years 2 and 3.

The major factor influencing cotton and grain sorghum yields was soil disturbance. Data are shown in Fig. 2 for cotton lint yields. The deep mix significantly out produced the control in years 1 and 2. The shallow mix out produced the control in years 1 and 3. The control soil produced the lowest yield each year. Sorghum grain yields followed the same trend (Data not shown). The site was not irrigated and the year to year difference in yield over experimental period was due to rainfall with 50.4, 29.2 and 38.0 inches of annual

Figure 2. Cotton lint yield for three years following disturbance of a Roetex clay soil. The shallow mix was to 2 feet and the deep mix was to 10 feet. Mean lint yields for a given year with the same letter are not different at the 0.05 level of significance.

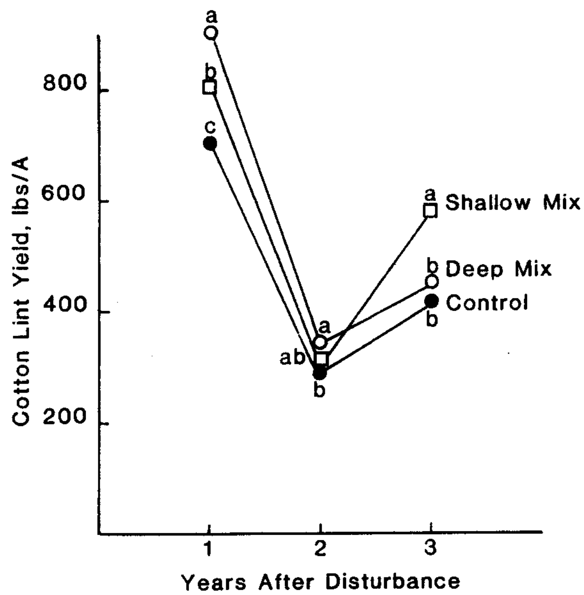


Table 2. Characteristics of soils and mixed overburden materials from the Brazos and Trinity River research site. Samples were from the top 6 inches of the original soil or the replaced overburden mix.

Parameter	Alluvial Valley				
	Brazos			Trinity	
		Shallow[†]	Deep[‡]		Deep[§]
Soil Series	Roetex	mix	mix	Kaufman	mix
pH	7.9	8.3	8.4	5.7	8.1
Organic Carbon, %	-	-	-	0.78	0.14
Electrical Conductivity, mmho/cm	0.32	0.37	0.34	0.40	0.40
Texture	clay	clay	clay	clay	sandy clay loam
Sand, %	5.0	4.0	4.8	4.8	63.7
Silt, %	48.1	46.7	38.8	22.2	11.1
Clay, %	46.9	49.3	56.4	73.0	24.2
Exchangable Cations					
Ca, me/100g	42.2	40.4	45.8	37.4	36.2
Mg, me/100g	3.3	4.5	4.2	5.1	1.1
K, me/100g	1.0	0.9	0.8	1.0	0.6
Na, me/100g	0.1	0.6	0.7	1.2	0.1

[†]Top 2 feet completely mixed and leveled.
[‡]Top 10 feet completely mixed and leveled.
[§]Top 20 feet completely mixed and leveled.

rainfall. The long-term average rainfall at the site is 34.4 inches.

Based on data generated over the three year period, it is concluded that mixing of overburden had a beneficial effect on the growth and yield of sorghum and cotton at comparable rates of fertilization. The increased yields are apparently due to greater rooting depth and a more favorable soil moisture condition created by the mixing of overburden materials. Deep plowing of Brazos River alluvial soils has been encouraged in the past to eliminate clay and plow pans present in the profile (Ford, 1970).

Trinity River Alluvial Site

Coastal bermudagrass (Cynodon dactylon (L.) Pers) is the most widely used, introduced, warm season perennial grass in Texas and is a primary forage grown on the heavy clay soils of the Trinity River alluvium. Hons et al. (1979, 1980) have demonstrated that Coastal bermudagrass is an excellent material for revegetation of mixed surface mine spoil generated from lignite mining activities.

Coastal bermudagrass yields on mixed alluvium were 23,000 and 21,000 lbs A^{-1} in years 3 and 4 following establishment of the grass, nearly double the yield of grass on the native Kaufman clay soil (Table 3). The decline in yield in year 5 was due to a reduction in N fertilization. Nitrogen was applied to Coastal bermudagrass at rates of 525, 400 and 300 lbs A^{-1} in years 3, 4 and 5, respectively. Total yields were excellent on both sites, with the mixed alluvium out-yielding the native soil each year, regardless of fertilizer N rates. Rainfall was well distributed and higher than the long-term average 39.4 inches in each year that productivity was measured.

Tree seedlings were planted and evaluated for survival from 2 to 4 years following establishment (Table 4). Green ash and Pecan readily established on the mixed alluvium. Green ash established reasonably well on the Kaufman clay but survival was significantly lower than on the mixed alluvium. Autumn olive, pecan, and water oak had survival values of only 36-40% when planted on the Kaufman clay.

Chemical and physical properties of the mixed alluvium were determined after 3 years in Coastal bermudagrass to determine changes with time (Table 5). Soil pH, cation exchange capacity, NO_3-N, and available P were not significantly different from the initial values after 3 years of fertilization and cropping. Significantly higher values were measured for total organic C, total Kjeldahl N, and NH_4-N. Electrical conductivity was low at 0.36 mmhos/cm but was significantly lower (0.19 mmhos/cm) after 3 years.

DISCUSSION

Yields of row crops and forage and tree survival were greater for mixed alluvium plots in both the Brazos and Trinity river sites.

Reasons for increased yields are apparently different at each site. Deep mixing of Brazos alluvium did not significantly change measured physical and chemical properties of the soil except that the clay content of the mixed alluvium was slightly higher. Clay and plow pans are common in these soils and previous research (Ford, 1970) has shown that deep plowing can increase crop yield, apparently due to deeper rooting as a result

Table 3. Coastal bermudagrass yields on an undisturbed Kaufman clay soil and on a deep mixed study soil at the Trinity River alluvial site.

Years following mixing	Forage Yield: Kaufman clay	Forage Yield: Mixed Alluvium[‡]	Difference
	lbs A^{-1}	lbs A^{-1}	
3	11,615a[†]	23,000b	11,385
4	10,475a	21,000b	10,530
5	11,740a	14,010a	2,270

[†]Means for a given year followed by the same letter are not significantly different at the 10% confidence level.
[‡] Mixed to a depth of 20 feet.

Table 4. Tree seedling survival on an undisturbed Kaufman clay soil and on a deep mixed study soil at the Trinity River Alluvial site.

Tree Seedling	Years after Planting	Survival: MixedAlluvium	Survival: Kaufman Clay	Probability (>t)
Green Ash	4	92	72	0.047
Autumn Olive	4	52	36	NS
Pecan	3	100	38	0.007
Water Oak	2	54	40	NS

of lower bulk density and soil strength and improved water relationships. Response of grain sorghum and cotton to fertilization was minimum and similar on all materials so fertility changes due to mixing were ruled out as a major contributing factor.

Increased forage yield at the Trinity River site is largely due to a textural change and improved physical conditions of the mixed alluvium. Mixing the top 20 feet of the profile reduced the clay content from 73.0 to 24.2% and increased the soil pH from 5.7 to 8.1. The Kaufman clay soil is commonly underlain by sand and gravel and has concentrations of $CaCO_3$ at depth. The Kaufman soil has limited potential for forage production (about 11,000 lbs A^{-1}) at high rates of N application. Mixing the alluvium resulted in a doubling in production potential for Coastal bermudagrass (23,000 lbs A^{-1}) at high rates of N fertilization (400-525 lbs N A^{-1}).

These data indicate that mixing of overburden located above lignite reserves in the Brazos and Trinity river alluvial valley floodplains may positively influence yields of row crops and forages and provide a better medium for the establishment of tree crops. An evaluation of the chemical and physical properties of the overlying sediments can be used to make this determination.

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Table 5. Changes in selected soil properties for the surface 0-12 inches at the Trinity River mixed alluvium study site after three years of Coastal Bermudagrass production.

Variable	Time: 0	Time: 3 years
pH	8.13 a†	7.90a
CEC, me/100g	21.70a	17.90a
Total organic C, %	0.14a	0.34b
Total Kjeldahl N, %	0.015a	0.103b
Electrical Conductivity, mmhos/cm	0.36a	0.19b
NH_4-N, mg kg-1	6.88a	3.36b
NO_3-N, mg kg-1	5.14a	7.54a
Available P, mg kg-1	6.17a	7.62a

† means for a given parameter followed by the same letter are not significantly different at the ten percent level of significance.

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Reclaimed Topography Effects on Small Grain Yields in North Dakota

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Abstract. Federal and state reclamation laws require separate handling of prime and nonprime soil materials. In the ustic moisture regime of North Dakota where lignite is mined, most prime soils occur on nearly level or concave portions of the landscape. This research was designed to determine topographic effects of reclaimed crop land on available soil water at planting and small grain yields. Data was collected for the years 1986 through 1991 at two locations. Although results for available water at planting showed different effects from year to year, overall mean values of both locations showed generally larger amounts for lower topographic positions (such as the footslope or toeslope) as compared to upslope positions (such as the shoulder). Small grain yields were likewise affected with downslope positions producing 30 to 80% higher yields than upslope positions when averaged over years. This indicated that landscape position played an important role in small grain yields. Thus, methodology to maximize water availability by adjusting topographic effects during reclamation will be a key to regulatory requirements of "equal to or better than" premining productivity levels.

INTRODUCTION

Federal and state reclamation laws require separate handling of prime and nonprime soil materials. In North Dakota, however, separate handling of subsoils is not required if it can be shown that the prime and nonprime subsoils are nearly uniform in physical and chemical properties.

In the ustic moisture regime of western North Dakota where lignite is mined, soils qualifying as prime almost always occur on nearly level or concave positions of the landscape. These topographic positions may receive runon water from upslope nonprime soils during rainstorms. This additional water input may then be available for vegetative growth.

Agricultural production in this area of North Dakota is highly dependent upon the amount of water available for plant growth. Bauer (1972) has shown that yields of small grains are highly correlated with available soil water at planting plus growing season precipitation. Bauer and Black (1991) have also measured and listed studies where (dependent upon soils, locations, management, and years) evapotranspiration may use from 5 to 20 cm of water before any grain is produced.

Several researchers have also indicated that landscape position influences crop yields (Ciha, 1984 and Stone et al., 1985). Hanna et al. (1982) documented how topography redistributed water among landscape positions through runoff-runon from precipitation. In addition, differences in saturated and unsaturated flow in the soil profiles also were shown to have an effect on the uneven distribution of water on the landscape.

This study was designed to determine the relationship of topographic position to available soil water at planting and small grain yields on reclaimed mineland soils. For ease of discussion, classical position terms (summit, shoulder, etc.) will be used although, by definition, they are not entirely applicable to reclaimed landscapes.

METHODS AND MATERIALS

This study was initiated at two reclaimed mineland locations in 1986. Discrete plots (30 by 30 m) were installed on four topographic positions (summit, shoulder, backslope, and footslope) at the BNI mine near Center, North Dakota. Each plot was separated from one another by 30 to 50 m of forages to minimize the possibility of runon water from upslope positions. The other location was established at the Falkirk Mining Company near Underwood, North Dakota. This was a continuous plot (approximately 400 by 30 m) utilizing seven topographic positions (summit; shoulder; top, middle, and lower backslope; footslope; and toeslope).

All tillage (fall chisel, spring disk) and planting operations were performed up and down the slope gradient. Fertilizer applications for a 2.7 Mg/ha yield goal were based upon soil testing and applied either by broadcasting and/or drill placement. Stoa wheat was seeded each year except 1988 when a Dumont oat crop was seeded (no yield data reported since the crop was lost to droughty growing conditions).

Two neutron access tubes for monitoring soil water by depth were installed in each topographic position. Available water at planting (AWP) was estimated from neutron attenuation measurements minus laboratory-determined 1.5 MPa wilting point values from the soil cores removed during access tube installation. Rainfall from planting to harvest was measured daily (1986 measurements were weekly) with a rain gauge located at each location. Total water use (TWU) was estimated for each topographic position by adding growing-season precipitation (GSP) to the change in profile soil water (0 to 1.2 m depth) from planting to harvest assuming no runon/runoff water from precipitation.

Small grain yields were based upon a 4m² sample (combining four 1m² samples) taken randomly near each access tube. This gave two replications per topographic position per year. AWP and yields were analyzed using a modified randomized block design. Regression/correlation procedures were used to relate yields to TWU.

RESULTS AND DISCUSSION

An average of 25 cm of loam topsoil over 80 cm of sandy loam was respread on the Center location. At Falkirk there was an average of 40 cm of silt loam topsoil over 70 cm of silt loam subsoil. Slope gradients at Center ranged from 1% (summit) to 9% (backslope) while at Falkirk values ranged from 0.5% (summit) to 9% (backslope).

Mean AWP values for the two locations are listed in Table 1. Significant differences among positions were generally found only in the first 3 or 4 years of the experiment. At Center the differences among positions was variable from year to year, most likely the result of drawdown of available soil water during the previous growing season and little soil water recharge over the winter. The large mean value for the shoulder position in 1986 was due to the presence of a large snowdrift forming on that position during the winter of 1985-86. Similar results were found for the Falkirk data, however the differences among positions within years did not vary as much as at Center. This would seem to indicate that some surface water movement was occurring at Falkirk, but not at Center because of the forage areas.

Table 1. Effect of topographic position on available water at planting for the reclaimed mineland locations.[1]

Position		Year of Data					
	1986	1987	1988	1989	1990	1991	Mean
				(cm)			
				Center			
Summit	13.8	16.9	7.0	7.7	5.9	4.8	9.3
Shoulder	23.2	12.1	6.4	9.5	6.6	6.2	10.7
Backslope	12.8	19.7	8.9	13.0	8.1	7.8	11.7
Footslope	18.6	14.2	3.0	16.3	4.9	6.4	10.6
LSD(0.10)[2]	1.4	2.6	3.0	4.1	NS	NS	1.1
		(For Position X Year Means: LSD(0.10) = 2.7)					
Year Means	17.1	15.7	6.3	11.6	6.4	6.3	——
			(For Year Means: LSD(0.10) = 1.4)				
				Falkirk			
Summit	12.9	14.8	9.6	4.2	3.5	3.2	8.0
Shoulder	7.6	9.1	4.5	1.5	1.1	1.3	4.2
Backslope -Top	14.8	14.5	11.5	5.2	4.4	3.3	8.9
-Middle	10.1	13.8	12.9	4.8	3.9	3.2	8.1
-Low	13.8	14.9	14.5	4.9	1.6	1.9	8.6
Footslope	16.8	16.0	12.0	7.3	4.6	4.6	10.2
Toeslope	16.8	15.9	10.2	8.1	3.7	3.9	9.8
LSD(0.10)	NS	3.4	4.5	NS	NS	NS	2.0
		(For Position X Year Means: LSD(0.10) = NS)					
Year Means	13.3	14.1	10.8	5.2	3.2	3.1	——
			(For Year Means: LSD(0.10) = 1.8)				

[1]Cumulative total for 0-1.2 m profile depth.

[2]Least significant difference at the P = 0.10 level. NS indicates no significant difference among mean values.

When averaged over years, AWP generally increased from upslope to downslope positions, although not always significantly. The shoulder position at both locations would have had the lowest mean values had it not been for the 1986 data at Center. Differences between the other positions (other than the summit) are generally nonsignificant.

Continuous cropping plus generally poor soil water recharge over the winter, resulted in an almost continuous and, sometimes, significant yearly decrease in mean location AWP values (Table 1). Although not shown, nearly all positions at both locations in 1991 had 50% or more of the total AWP in the 0.6 to 1.2 m profile depth. Variability in the data for the comparisons of the position by year data was the main factor contributing to the presence or lack of significant differences.

Table 2 shows that GSP also was highly variable from year to year at each location. The Center location never exceeded the long-term average for that location while 3 of 5 years at the Falkirk location were above average. Very few daily rainfall totals exceeded 2.5 cm at either location over the years shown.

Table 2. Growing-season precipitation measured at the two topography locations.

Location		Year of Data[1] 1986	1987	1989	1990	1991
				(cm)		
Center	Received	17.6	19.4	12.5	20.4	——
	Deviation[2]	-1.2	-2.6	-7.8	-2.9	——
Falkirk	Received	22.6	28.2	11.8	25.0	18.6
	Deviation	+0.8	+4.8	-11.0	+0.4	-5.6

[1]An oat crop seeded in 1988 was lost to drought at both locations. Center wheat crop in 1991 lost to hail.
[2]Deviation from 30-year average amounts from nearby NOAA weather stations.

Table 3. Effect of topography over years on wheat yields at the two locations.

Position/Mean	Year of Data[1] 1986	1987	1989	1990	1991	Mean
			(Mg/ha)			
			Center			
Summit	1.31	0.51	0.58	1.00	ND[2]	0.84
Shoulder	1.37	0.40	0.57	0.96	ND	0.80
Backslope	1.24	0.36	0.62	1.32	ND	0.88
Footslope	1.74	1.31	1.46	1.31	ND	1.49
LSD(0.10)[3]	0.17	0.20	0.18	0.14	——	0.11
		(For Position X Year Means: LSD(0.10) = 0.22)				
Year Means	1.41	0.63	0.81	1.16	——	——
		(For Year Means: LSD(0.10) = 0.11)				
			Falkirk			
Summit	1.49	1.13	0.63	1.86	1.51	1.30
Shoulder	1.13	1.14	0.53	2.31	1.48	1.31
Backslope -Top	1.59	1.22	0.86	2.36	1.57	1.52
-Middle	1.88	1.67	0.79	2.57	1.65	1.74
-Lower	1.63	1.40	0.94	2.26	1.70	1.54
Footslope	2.33	1.76	1.03	2.48	1.84	1.88
Toeslope	2.24	0.91	1.09	2.60	1.94	1.79
LSD(0.10)	0.25	0.28	0.18	0.27	0.16	0.12
		(For Position X Year Means: LSD(0.10) = 0.28)				
Year Means	1.76	1.32	0.84	2.33	1.67	——
		(For Year Means: LSD(0.10) = 0.10)				

[1]An oat crop grown in 1988 was lost to drought.
[2]Crop lost to hail.
[3]Least significant difference at the P = 0.10 level from analysis of variance.

Mean wheat yields at both locations showed significant topographic position effects for each year of this experiment (Table 3). While differences among positions at both locations varied from year to year, the lower slope positions generally had higher yields than upslope positions. The presence of the snow accumulation on the shoulder position at Center in early 1986 resulted in a fairly large yield for that year, while the trend during latter years showed this position yielded less than the other positions. At Falkirk in 1987, the toeslope was accidently double-seeded causing a reduced yield.

Significant differences in mean yearly average yields were also present at each location. Much of these differences were attributed not only to the significant differences between years for AWP, but also to the amount and distribution of GSP. For example, AWP and GSP for Falkirk in 1987 were both larger than 1990, but yields were significantly greater for 1990 than 1987. This was true for other comparisons among years as well.

Position mean wheat yields generally showed that downslope positions had significantly larger yields than upslope positions, especially when averaged over time. At Center, for example, the footslope position yielded nearly 70 to 86% more than the upslope positions. The increases in yields at Falkirk were not as high and may be due to more uniform distribution of runon/runoff water on its continuous plot verses the effect on runon/runoff of the discrete plots used at Center. A small surface indentation that may have influenced surface water distribution away from the lower backslope position at Falkirk was believed to have contributed to decreased mean yields over years for that position. Had the toeslope not been double seeded in 1987 at Falkirk, it is likely that its mean yield over years may have been greater than the footslope position, although the means may not have been significantly different.

An attempt was made to relate wheat yields to TWU and these results are shown in Table 4. All parameters are significant at the 10% level while the equations are significant at the 0.01% level. However, less than half of the variability in yields could be accounted for by TWU.

SUMMARY

Reclaimed minelands at two locations were used to study topographic position effects on available water at planting and small grain yields over a number of years. Both locations had fairly uniform topsoil and subsoil depths among positions although one location used discrete plots and the other used a continuous plot. Available water at planting initially showed some significant effects among positions, but these differences were nonsignificant due to variability in latter years from continuous cropping and droughty growing conditions. Wheat yields both within and over years generally increased (although not always significantly) at both locations from upslope to downslope positions. Regression analyses indicated a poor correlation between yield and total water use (assuming no runon/runoff). The somewhat low R^2 values may have been caused by differences between years in the distribution of growing season rainfall, runon/runoff, and yield variability. The data did indicate, however, that topographic position played a significant role in yields. This may be as important as the presence or lack of prime soil materials in certain topographic positions.

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Table 4. Regression/correlation analysis results from the two reclaimed mineland locations relating wheat yields to total water use.[1]

		Regression Coefficients				
Location	N	a	b	Intercept	R^2	MSE
Center	32	0	0.055	-0.040	0.47	0.11
Falkirk	70	-0.005	0.270	-1.871	0.44	0.20
Combined	102	-0.003	0.212	-1.459	0.47	0.20

[1] Equation Form: Yield (Mg/ha) = $(a*TWU^2) + (b*TWU)$ + Intercept, where TWU = total water use, cm.

Relationship of Soil Strength and Rowcrop Yields on Reconstructed Surface Mine Soils

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Abstract. The soil reconstruction process varies in methods of excavation, transportation and placement. The resulting variability in productivity is difficult to assess and most research and regulatory efforts rely on long-term and short-term (two or three crop years) yield monitoring. A method of assessment that uses the relationship of soil physical properties to long-term yields will eliminate the varibility of yearly weather patterns which often affect short-term yield monitoring. Soil strength measurements to a 44 inch depth were recorded from the harvest sites at three prime farmland reclamation research plots in southwestern Illinois. The plots include a wide range of reclamation methods, including deep tillage. Data from row-crop yields, as well as, soil physical properties has been collected for 5-11 consecutive years, depending on the site. Soil strength was highly correlated to yield means at the research sites. The results also indicate possible upper and lower thresholds where other soil parameters may become dominate in determining yield.

INTRODUCTION

Current reclamation practices include a variety of methods to reconstruct soils. The methods of excavation, transportation, and placement can affect the physical properties of the reconstructed soil. This is a major factor affecting crop performance (Jansen, et al., 1985). The relationship of compacted subsoils and poor crop performance has been identified with deep tillage to relieve subsoil compaction and improve productivity becoming an accepted practice in the industry. Though deep tillage is commonly used, in southwestern Illinois, as the final step in the reclamation process for row-crop acres, the yield effects of tillage depth and time are currently being studied (Dunker, et al., 1990). Productivity is currently determined with yield measurements for 2 or 3 crop years out of ten, and is based on land use classification (Ill. Adm. Code 1816.116). Though this method includes a factor of time, it is subject to variable weather patterns across those years. It also compares an average for a large area (county) to a single field. Weather variability within a year and across the county could fall in favor or against either the mine operator or the landowner. The continuous monitoring of yields over a 10 year period would be an unmanageable burden, though just as time consuming. This also would not conform to normal crop rotation management in some areas. There is a need to more closely define the relationship of physical properties of the soil to long-term yields. The determination of an acceptable soil physical, as well as, chemical condition, perhaps along with some confirming yields, would certainly improve the reliability of the productivity test.

A constant rate penetrometer was developed to serve the need to quantify physical properties of reconstructed soils (Hooks and Jansen, 1986). Thompson, 1987, studied the relationship of bulk density and soil strength to corn root length density on reclaimed soils. That study concuded that while both bulk density and soil strength correlated well with corn root length density, soil strength data was easier to collect in the numbers required to accurately assess reconstructed soils. Bulk density sampling is questionable on reclaimed soils, especially deep tilled soils. In some cases, there is a resultant fluff in the soil that may be as much as 20 inches. With this dramatic increase in macroporosity, percolation increases and the subsoil can be easily compressed. The reliability of in situ soil strength measurements has been questioned (Mulqueen, et al., 1977). Mulqueen also acknowledged the ease of sampling and suggested the measurement of moisture content. Perumpal, (1983), presented a summary of many studies with the cone penetrometer. These studies relate the effects of moisture content, density , texture and even organic matter to cone index. It appears that it is generally accepted that soil strength measurements are most reliable at or near field capacity. From an engineering or physical approach, soil strength is a true value that should be predictable with given values of moisture content, texture, density, etc. In this study, soil strength is approached as a relative value that is a composite of the effects of moisture content, texture, density, etc. Moisture content is a major factor in soil strength when it is well below field capacity. However, when the data is collected in the spring, when soils are the most uniformly moist, minor differences in soil moisture between treatments are, in this study, considered to be a reflection of the soil/environment interaction and a valid part of the composite value "soil strength". Comparisons are made between adjacent treatments on a plot or closely located plots that are under the same tillage/crop management and subject to equal weather conditions.

METHODS

Soil strength measurements with the constant rate recording penetrometer (Hooks and Jansen, 1985) were recorded on three reclamation research plots. Data was taken in the spring when soils are uniformly moist to minimize the effects of variable soil moisture on penetration resistance. Sampling at each location consisted of four samples to a depth of 44 in per treatment replicate with two sub-samples per sample. The penetrometer samples sites correspond to the harvest sites for yield determination. Subsamples are are averaged for each of the 50 readings that make up a depth profile to leave one average profile per sample. The average profile for each sample is then broken down into five depth segments and an average penetrometer resistance reading is calculated that represents 9 in of the total profile. Penetrometer depth segments are:

Segment 1	0-9 in
Segment 2	9-18 in
Segment 3	18-27 in
Segment 4	27-36 in
Segment 5	36-44 in

Segment 1 is not used in the analysis because it covers the conventional tillage zone and has been altered from its original condition.

Penetrometer measurements on mined land has resulted in wide ranging values between reclamation treatments. These correspond to wide ranging values in crop yield. In general, reclamation treatments with high levels of soil strength (compaction) have had the lowest crop yields, while those treatments with low soil strength have had the highest yields. Correlation of penetrometer resistance with yield has been significant in most years for both corn and soybeans. The purpose of these analyses is to determine the relationship of penetrometer resistance data with long term yield results.

RESULTS AND DISCUSSION

Two experiments were selected for the first database, the Captain Mix and the Denmark truck plots in Perry County. These plots were selected for two reasons: 1) Because the mines are adjacent, the weather and natural soils used in the reclamation process are similar. 2) These two experiments represent a range in yield and penetrometer values necessary for meaningful correlation between soil strength and yield response. Corn hybrids, fertility, and tillage management of these were the same. Consequently, any differences in yield variation can be associated to soil reclamation differences.

1985-90 mean corn yields and mean penetrometer resistance values averaged over the 9-44 in depth are presented in Figures 1 and 2. Response is similar to that observed in individual years. Yield decreases with increasing soil strength. Treatments represented are; MIX, mean values for all treatments using the wheel-

Figure 1. 1985-90 mean corn yields and soil strength (9-44 in Avg) of Captain Mix and Denmark Truck plots.

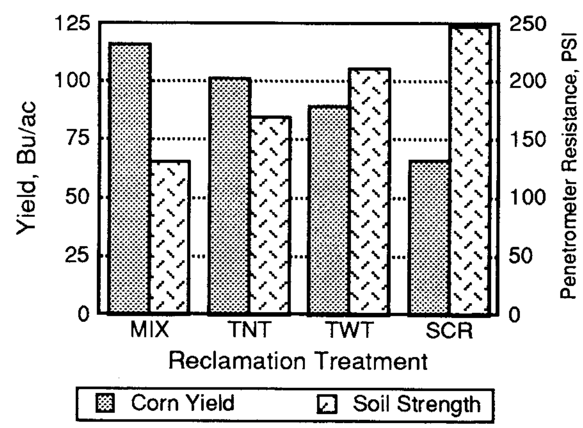
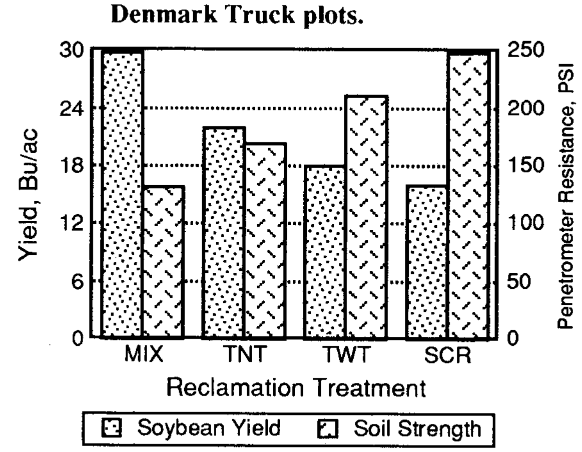


Figure 2. 1985-90 mean soybean yields and soil strength (9-44 in Avg) of Captain Mix and Denmark Truck plots.



conveyor spreader method of soil construction; TNT, truck hauled rooting media with truck traffic restricted to operating on the base spoil; TWT, truck hauled rooting media with truck traffic on root media surface; SCR, scraper hauled root media.

Correlation of penetrometer resistance by segment depths and profile means (9-44in) with six year crop yield means show the significant relationship of soil strength to yields of both corn and soybeans (Table 1). Within the observed values of this experiment across a six year period, soil strength is significantly correlated to corn and soybean yield in all depth segments. Figure 3 shows the relationship between average penetrometer resistance for the 9-44 in segments and 6 year mean rowcrop yields. This relationship of yield and soil strength is curvilinear. A curvilinear response would be expected because as soil strength decreases, yield can increase to only a certain potential level. In contrast, as soil strength increases to a level which prohibits root penetration by mechanical impedance, any additional increase in soil strength would have no effect on yield.

The site for the second database is at the Burning Star #2 mine , about 20 miles northeast of the of the first location. The plots are a deep tillage experiment on scraper placed soil. It is a randomized complete block design with 6 blocks and, at the time of the study, 6 treatments:

Treatment	Tillage Depth
CHS	8 in
TG2	14 in
RM1	32 in
TLG	32 in
DM1	48 in
DM2	48 in

Table 2 presents correlation data of soil strength with corn and soybean yield for 1988, 1989, and 1990. Correlation of penetrometer resistance by segment depths and profile means (9-44 in) to mean yields both within and across years show the significant relationships of soil strength and crop yields. Three year mean corn yields are highly correlated with penetrometer resistance of the deeper profile depth segments (27-36 in and 36-44 in) and of the average 9-44 in soil profile depth. Two year mean soybean yields also show significant correlations with soil strength at the deeper depths (27-36 in and 36-44 in). Weather variation has confounded interpretation within and among years. Soybean yields have been negatively affected in both 1988 and 1989 by above normal temperatures and below normal rainfall in late August and early September. Soybean yields for both years can be characterized as poor due to this weather stress. Even though soybean yields are low, significant yield effects due to tillage and soil strength have occurred.

Figure 4 presents the relationship of 1988-90 mean corn yields to two year mean soil strength values averaged over the 9-44 in depth. The relationship of yield and soil strength is curvilinear. As with the first database, curvilinear relationship is expected because as soil strength decreases, yield can increase to only a certain potential level. In contrast, as soil strength

Table 1. Correlation of logarithmic means of 1985-90 crop yields and penetrometer resistance from Captain Mix and Denmark Truck treatments.

Depth Segment	Corn	Soybeans
	Correlation Coefficient	
9-18 in	-0.97*	-0.91+
18-27 in	-0.96*	-0.99**
27-36 in	-0.96*	-0.99**
36-44 in	-0.96*	-0.99**
Ave 9-44 in	-0.98*	-0.99**

**, Statistically significant at the 0.01 level
*, Statistically significant at the 0.05 level
+, Statistically significant at the 0.10 level.

Figure 3. Regression of 1985-90 mean yields of Captain Mix and Denmark Truck treatments to 9-44 in average soil penetrometer resistance.

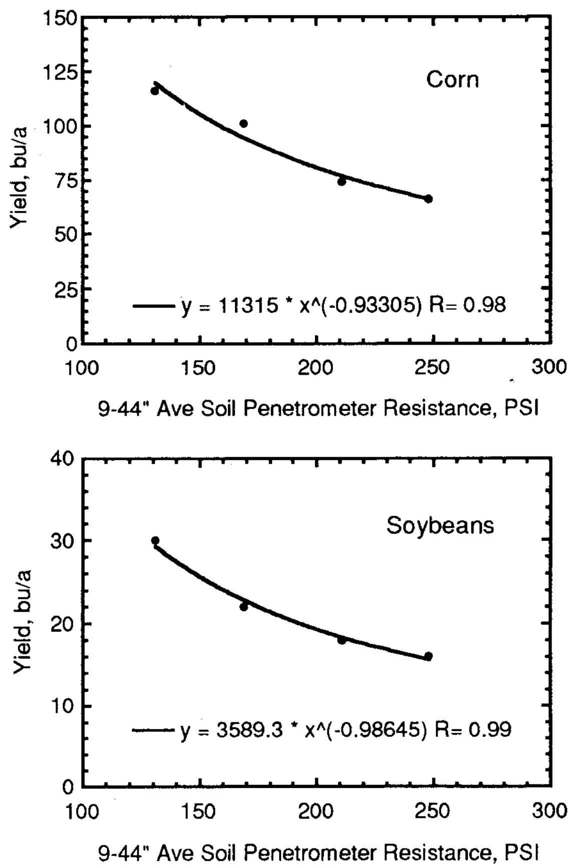
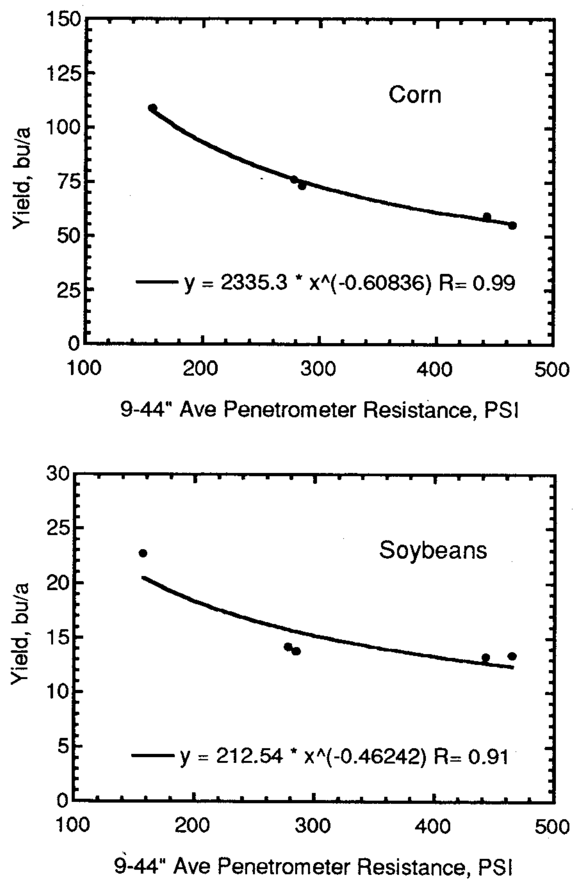


Figure 4. Relationship of penetrometer resistance and 1988-90 crop yields at Burning Star #2.



increases to a level which prohibits root penetration by mechanical impedance, any additional increase in soil strength would have no effect on potential yield. It appears that soil strength measurements with the deep profile penetrometer is a viable method for assessing long term yield potential of mined land when other chemical and plant nutritional variables are not yield limiting factors. While yield variation among years is associated more closely to weather variables than to soil factors, soil strength appears to be closely correlated to mean yields averaged over multiple years.

Significant differences in yields of the experimental blocks have occurred. Blocks 1-3 on the west side have yielded lower than blocks 4-6 on the east side. Pre-tillage evaluation with the cone penetrometer shows significant initial differences in soil strength between the east and west sides of the plots. Soil strength levels of the west side were significantly greater than the east blocks for each depth segment and for the average 9-44 in profile depth (Fig. 5). Post-tillage penetrometer data shows similar trends (Fig. 6). Note that the relationship of soil strength and tillage depth is consistent on both sides. Reduction of soil strength with increasing tillage depth is occurring at the same rate, only the magnitude of soil strength is different. This data suggests that the effect of tillage in reducing soil strength levels is affected by initial levels of compaction. The practical application of this finding is that compaction is better prevented than cured.

Yields of corn and soybeans comparing the east and west sides within and across years show that significant yield differences have been observed within treatments (Table 3 and Table 4). Mean corn and soybean

Table 2. Linear correlations (logarithmic transformation) between yield and penetrometer resistance for treatment means.

Segment Depth	1988	1989	1990[1/]	88-90
			Corn	
9-18 in	-.87*	-.81*	-.59	-.71
18-27 in	-.93*	-.85*	-.60	-.84+
27-36 in	-.86*	-.97**	-.93**	-.98**
36-44 in	-.73	-.93*	-.98**	-.91*
Ave 9-44 in	-.98**	-.98**	-.85*	-.97**
			Soybeans	
9-18 in	-.41	-.59		-.42
18-27 in	-.61	-.60		-.59
27-36 in	-.98**	-.91**		-.97**
36-44 in	-.97**	-.99**		-.99**
Ave 9-44 in	-.81+	-.87*		-.82+

[1/]Soybeans were not harvested in 1990

**, Statistically significant at the 0.01 level

*, Statistically significant at the 0.05 level

+, Statistically significant at the 0.10 level.

yields of the west (blocks 1-3) and east (blocks 4-6) sides have been significantly different for each year and when averaged across years. These yield differences are highly correlated to soil strength levels within each side. This data suggests that the initial level of compaction, i.e. soil strength, will affect the depth of tillage needed to achieve productivity. Three year mean corn yields of the TLG and RM1 on the lower soil strength east side blocks are comparable to the adjusted target yield values for the permit area, while the corn yields on the higher soil strength west blocks are several bushels

Figure 5. Comparison of pre-tillage soil strength of west blocks(1-3) and east blocks(4-6).

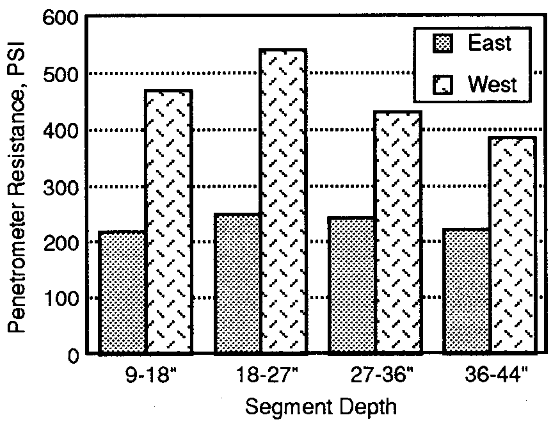


Figure 6. Comparison of tillage treatments on 9-44 in ave soil strength of west blocks(1-3) and east blocks(4-6).

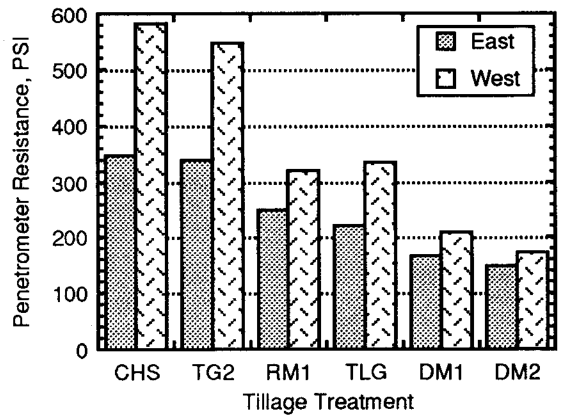


Table 3. Corn yields comparing blocks 1-3 (west side) to blocks 4-6 (east side).

				Tillage Treatment			
Blocks	CHS	DM2	DM1	RM1	TG2	TLG	Mean
				Yield, bu/a			
				1988			
East (4-6)	48.2 a[1/]	-	91.9 a	65.6 a	47.5 a	77.0 a	66.0 a
West (1-3)	25.8 b	-	82.2 a	45.6 b	37.8 a	58.4 b	50.0 b
				1989			
East (4-6)	58.4 a	142.9 a	128.4 a	92.7 a	61.0 a	93.5 a	96.2 a
West (1-3)	63.3 a	142.3 a	125.1 a	79.4 b	44.1 b	73.1 b	87.9 b
				1990			
East (4-6)	102.2 a	154.3 a	137.4 a	106.1 a	104.7 a	109.7 a	119.1 a
West (1-3)	21.9 b	78.8 b	75.4 b	39.4 b	55.5 b	26.1 b	49.5 b
				1988-90 Mean			
East (4-6)	69.6 a	-	119.2 a	88.1 a	71.1 a	93.4 a	88.3 a
West (1-3)	37.0 b	-	94.2 b	54.8 b	45.8 b	52.5 b	56.9 b

1/ Yield values followed by the same letter within a tillage treatment and year are not significantly different at the 0.05 level.

Table 4. Soybean yields comparing blocks 1-3 (west side) to blocks 4-6 (east side).

				Tillage Treatment			
Blocks	CHS	DM2	DM1	RM1	TG2	TLG	Mean
				Yield, bu/a			
				1988			
East (4-6)	14.2 a[1/]	-	20.5 a	14.6 a	13.4 a	15.4 a	15.6 a
West (1-3	13.1 a	-	21.7 a	12.7 b	11.7 a	12.9 b	14.4 b
				1989			
East (4-6)	17.8 a	34.9 a	31.4 a	18.4 a	16.4 a	18.4 a	22.9 a
West (1-3)	8.7 b	25.5 b	17.3 b	9.4 b	9.7 b	10.0 b	13.4 b
				1988-89 Mean			
East (4-6)	16.0 a	34.9 a	25.9 a	16.5 a	15.0 a	16.9 a	19.6 a
West (1-3)	10.9 b	25.5 b	19.5 b	11.1 b	10.7 b	11.5 b	13.9 b

1/ Yield values followed by the same letter within a tillage treatment and year are not significantly different at the 0.05 level.

lower. Only the DMI deep plow treatments produced two and three mean yields comparable to base and adjusted target yields on the west side. Soybean yields for all tillage treatments on the west blocks were significantly lower than those obtained on the east blocks. However, soybean yields of the DMI deep plow treatments on both the east and west blocks were comparable to the permit area target yields.

Regression of mean soil strength values of the three east blocks and the three west blocks with mean 1988-1990 corn and soybean yields of the east and west blocks (Fig. 7 and 8) show decreasing yields with increasing soil strength levels. This analysis, which separates the effects of the east and west blocks, shows that the penetrometer is successful in identifying these effects. The logarithmic regression model of soil strength with yield explained 92% of the variation in three year mean corn yields (R^2=.92) and 81% of the variation in two year mean soybean yields (R^2=.81).

Particle size analysis of treatments within the east and west blocks reveal differences in texture (Table 5). Clay content of the rooting media of the east blocks average approximately 5% more than the west side. All treatments in the east side blocks fall within the clay loam textural class. The west side has a higher proportion of coarse particles and texture ranges from silt loam to loam. The effects of texture differences on crop productivity and soil strength, if any, for this narrow range of particle size, is speculative at this point. Comparison of particle size to soil strength profiles within each plot has not resulted in any significant correlation. However, coarse fragments were not included in the analysis. Coarse textured Illinoian till is observeably the dominant subsoil material in the west blocks. The dominate subsoil material in the east blocks is noticeably finer textured, loess (B horizon), higher in clay. Further study is certainly needed to define the effect of particle size variability on yield and it's role in the soil strength/yield relationship.

Figure 7. Regression of Blocks 1-3 and Blocks 4-6 mean soil strength with 1988-1990 mean corn yields of blocks 1-3 and blocks 4-6.

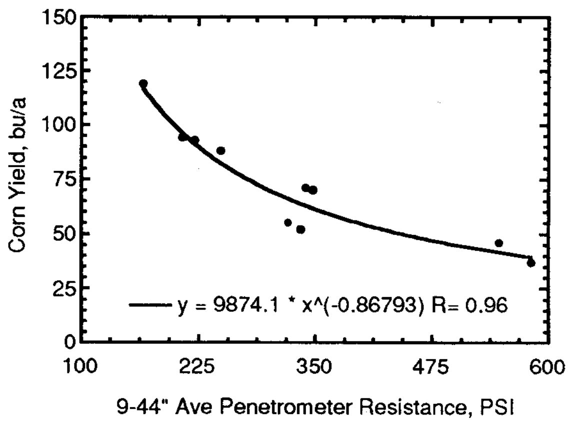


Figure 8. Regression of Blocks 1-3 and Blocks 4-6 mean soil strength with 1988-1989 mean soybean yields of blocks 1-3 and blocks 4-6.

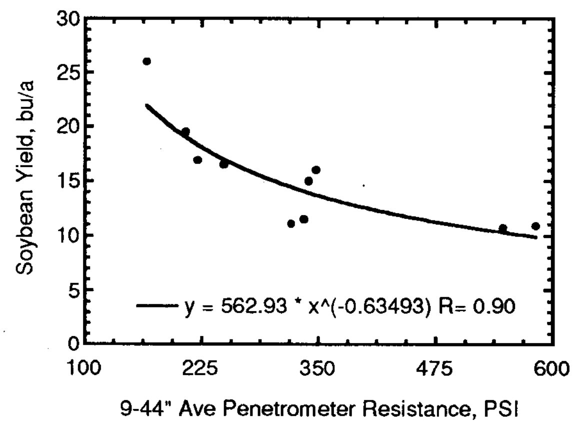


Table 5. Soil test results of rooting media (24 in depth) comparing blocks 1-3 (west side) to blocks 4-6 (east side).

TRT	Side/Blocks	% Sand	Particle Size % Silt	% Clay	Texture Class
CHS	East (4-6)	24.2	48.0	27.8	clay loam
	West (1-3)	22.4	57.1	20.5	silt loam
DM2	East(4-6)	23.1	49.4	27.4	clay loam
	West (1-3)	28.4	50.3	21.2	silt loam
DM1	East(4-6)	23.2	50.4	26.4	silt loam
	West(1-3)	26.3	50.8	22.8	silt loam
RM1	East(4-6)	28.7	43.9	27.4	clay loam
	West(1-3)	30.3	46.6	23.3	loam
TG2	East(4-6)	25.5	46.6	27.8	clay loam
	West(1-3)	23.4	54.1	22.5	silt loam
TLG	East(4-6)	23.7	47.4	29.3	clay loam
	West(1-3)	28.2	47.0	24.3	loam
All Trts	East(4-6)	24.9	47.6	27.4	clay loam
	West(1-3)	26.2	51.3	22.4	silt loam

It appears that soil strength measurements with the deep profile penetrometer is a viable method for assessing long term yield potential of mined land when chemical and plant nutritional variables are not yield limiting factors. While yield variation among years is associated more closely to weather variables than soil factors, soil strength appears to be closely correlated to mean yields averaged over multiple years. If this system is to be used as the basis of minesoil evaluation, it must be able to determine the relationship of penetrometer resistance and long term yields over a wider range of soil strength and yield values and a wider geographical application. To address this, the two databases were combined to provide the expanded range in observed values. Pre-mine soils of these areas are similar, corn hybrids were the same, and fertility was at a level not limiting yield. Yield values over a common three year period (1988-90) were used in the analysis. Penetrometer data was comprised of mean values over multiple years and all penetrometer readings were taken in early spring when soils were at or near field capacity. Results of this analysis show that corn yields decreased with increasing soil strength levels (Figure 9). Regression analysis (Figure 10) using a double logarithm model (log of yield and log of penetrometer resistance) showed that 88% (r^2=.88) of variation in observed yields was accounted for by the regression model. Correlation of soil strength (r=-.94)and three year mean corn yield was highly significant (0.01 level).

SUMMARY

Soil strength is highly correlated to corn and soybean yields on reconstructed soils. The response is curvilinear with yield decreasing as soil strength increases. Though it is not clearly defined by this study, there appears to be upper and lower thresholds to the effect of soil strength on yield. At the upper limit, somewhere near 300 PSI, any further increase has minimal yield effects which would be logical since mechanical impedence of root penetration retricts the soil volume that the plant can explore to a minimum. Below this level of soil strength, there is an area where the soil volume that the plant can explore is variable and relative to soil strength; the zone of maximum yield response to soil strength. Below this level, somewhere near 100 PSI, lies an interesting zone that warrants further study. At this point mechanical impedance is at a minimum, the rooting volume apparently does not increase dramatically. Yet, significant differences in yield may occur. It is suggested that the quality of subsoil materials, which would be determined by the pre-mine soils as well as reclamation practices, may become a dominate influence to any further increase in yield.

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Figure 9. 1988-90 mean corn yields and penetrometer resistance values from Captain Mix, Denmark Truck and BS #2 plots.

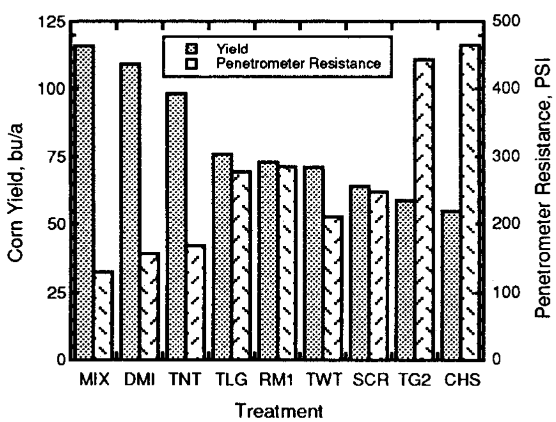
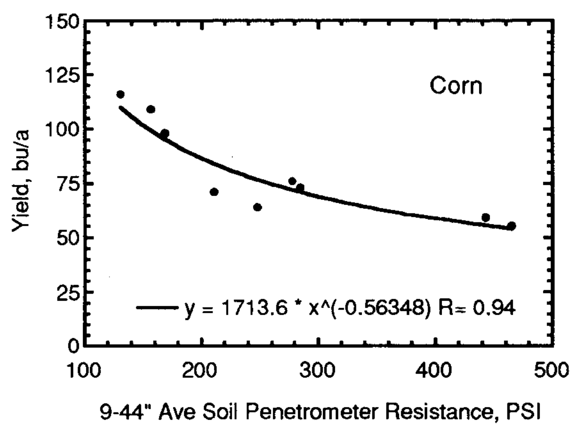


Figure 10. Regression of 1988-90 mean corn yields to 9-44" average soil strength of Captain Mix, Denmark Truck and Burning Star #2 treatments.



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Reconstructed Soil Depth for Rowcrop Production on Reclaimed Prime Farmland in Southeast Kansas

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Abstract. A three year study was conducted to determine the effects of reconstructed soil depth and ripping on grain sorghum (Sorghum bicolor (L.), Moench) and soybean (Glycine max (L.), Merr) yields on reclaimed prime farmland in southeast Kansas. Experimental plots were constructed with 30 cm of topsoil placed over 0, 30, 60, or 90 cm of subsoil on graded minespoil. One half of each plot was ripped to a 51 cm depth prior to planting the first year. Except for grain sorghum in the third year when drought conditions persisted throughout the growing season, subsoil replacement had little effect on rowcrop yields at this site. Third year grain sorghum yields were significantly increased when 30 cm of subsoil was placed under 30 cm of topsoil. Further increases in yield with 60 or 90 cm of subsoil under topsoil were not significant. A significant yield response to ripping was measured for soybeans the first year and was attributed to improved drainage of the upper portion of the soil profile during an unseasonably wet year. A significant response to ripping was also observed for grain sorghum in the third year. The overall poor yields and lack of response to subsoil replacement of grain sorghum and soybeans at this site are attributed mainly to poor soil physical conditions which result from compaction by scrapers during the soil reconstruction process.

INTRODUCTION

Surface mining in southeast Kansas has occurred on historically productive agricultural soils, many of which meet the criteria for designation as prime farmland. Reclamation plans for prime farmland are crafted so that an equal or higher level of productivity can be demonstrated on reconstructed soils compared to soils that existed prior to mining. Such plans must create new soils capable of supporting intensive agricultural production as dictated by state and federal regulations. To meet this objective special attention is given to the separate removal and respreading of subsoil and topsoil over leveled minespoil, creating a plant growth medium similar to the soils that were in place prior to mining. Reclamation research during the past two decades has shown this method to be the most effective means of restoring productivity to lands affected by surface mining (McGinnies and Nicholas, 1980; Merrill et al., 1980; Halvorson and Doll, 1985).

Determination of soil depth requirements for successful reclamation of mined lands has been the subject of many experiments in the Northern Great Plains and in the more humid regions of the Midwest. In the Northern Great Plains where saline and sodic spoils are frequently encountered, research has focused primarily on revegetation with native grasses and forages (Power et al., 1974; Merrill et al., 1985), and spring wheat production (Power et al., 1981). A majority of experiments in this region have obtained maximum yields at total soil depths ranging from 46 cm to 120 cm (Redente and Hargis, 1985; Barth and Martin, 1984; Power et al., 1981). On more favorable non sodic spoils, differences in soil depth requirements have been attributed to the effects of topsoil, subsoil, and spoil texture on the available water holding capacity of the reconstructed soil (Halvorson et al., 1986; Halvorson et al., 1987).

Soil thickness on reclaimed prime farmland in the more humid Interior Coal Province do not appear to differ greatly from those in the more arid West. In Illinois, maximum corn and soybean yields were obtained when 80 cm of good quality soil was placed over favorable spoil material (Jansen et al., 1984). Increases in yield were not observed at soil depths greater than 80 cm because roots were unable to penetrate beyond a 60 cm depth, regardless of the depth of soil. They noted that because of shallow rooting, the maximum yields were still very poor. In Kentucky, researchers obtained highest yields of winter wheat on at least 50 cm of topsoil (Barnhisel et al., 1988), and highest grain sorghum yields with between 40 and 80 cm of subsoil plus 20 cm of topsoil placed over limed acid spoil (Barnhisel et. al, 1987).

Crops grown on reconstructed soils may be more susceptible to temperature and moisture stress than those on undisturbed soils, likely because of increased soil strength as a result of compaction during soil reconstruction (Indorante et al., 1981; Indorante et al., 1984). In mining operations where there is excessive traffic during soil reconstruction, the benefits of constructing deeper soils may be masked by excessive compaction. Subsoiling may aid in reducing the negative impact of compaction on plant growth. Much of the research on subsoiling has been on undisturbed soils having either a natural or tillage-induced hardpan capable of impeding root growth (Robertson et al., 1957; Patrick et al., 1959; Ide, et al., 1984; Kamprath et al., 1979). In most studies, favorable responses to subsoiling occur only when plants would otherwise suffer from moisture deficit during periods of below normal or poorly distributed precipitation. Where reconstructed prime farmlands are concerned, lessening the severity of moisture stress could be beneficial to the attainment of required target yield levels.

In Kansas, reclamation research has occurred primarily on land disturbed prior to enactment of state reclamation legislation in 1968. Most efforts have dealt with reforestation, rangeland establishment, and cereal grain production on leveled or recontoured spoil banks (Camin et al., 1972; Geyer, 1972). Current reclamation laws require that prime agricultural soils be reclaimed by replacing at least 120 cm of soil over graded minespoil unless alternative procedures can be proven just as effective in achieving the desired post-mining level of productivity. This research was initiated with the objectives of determining rowcrop yield response to different depths of reconstructed soils and determining if ripping the reconstructed soils will improve crop yields.

MATERIALS AND METHODS

Experimental plots were constructed in the fall of 1985 at P & M Midway mine located in Linn county, southeast Kansas. The climate in this region is continental, having a total annual rainfall of about 980 mm, of which about 70 percent normally falls April through September. The pre-mine soil in the study area was mapped as a Parsons silt loam (Fine, mixed, thermic Mollic Albaqualf) with nearby occurrences of Dennis silt loam (Fine, mixed, thermic Acquic Paleudoll) (USDA Soil Conservation Service, 1981). Twelve plots with dimensions of 54 m x 54 m were constructed using P & M Midway scraper pans and bulldozers for all soil transport and placement. Topsoil and subsoil materials were taken from existing stockpiles of A and B horizons as separated during the mining operation. Each reconstructed soil consisted of 30 cm of topsoil placed over 0, 30, 60, or 90 cm of subsoil on graded minespoil. The subsoil depth treatments were arranged in a randomized complete block design with three replications. On 7 March 1986 one - half of each block was ripped with a chisel-type subsoiler to a depth of about 51 cm. The overall experimental design was a split-plot with ripping as the whole plot and subsoil depth as sub-plots arranged in strips. Crops were randomly assigned to a 9 m x 54 m strip on each subsoil depth treatment, perpendicular to the direction of ripping, so that each crop contained a ripped and unripped treatment. The rowcrops included in the study were grain sorghum (Sorghum bicolor (L.), Moench), hybrid 'Paymaster DR1125', and soybean (Glycine max (L.), Merr), variety 'Pershing'. Two strips on each plot were seeded to soybean the first year to establish a grain sorghum-soybean rotation for comparison to continuous grain sorghum. Crops were planted in 75 cm rows each year at seeding rates of 173,000 seeds ha^{-1} for grain sorghum and 430,000 seeds ha^{-1} for soybeans on Jun 30, June 9, and June 18 in 1986, 1987, and 1988, respectively.

Soybeans received diammonium phosphate as starter fertilizer banded below and to the side of the seed at rates of 112 kg ha^{-1} each year. Weeds were controlled using a mixture of metribuzin, 4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one and alachlor, 2-chloro-2',6'-diethyl-N-(methoxymethyl)acetanilide, applied at labelled preemergence rates. Prior to planting each year, grain sorghum received broadcast applications of N at rates of 105 kg ha^{-1} each year. At planting, diammonium phosphate was banded below and to the side of the seed at a rate of 112 kg ha^{-1}. Weeds in grain sorghum were controlled with a mixture of metolachlor, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl acetamide, and atrazine, 2-Chloro-4-ethylamino-6-isopropylamino-1,3,5 triazine, applied preemergence at label-recommended rates. Yields of both crops were taken from interior rows of all plots and threshed at the site with a portable thresher. Harvested areas in 1986 and 1988 were 6.75 m^2 and 4.50 m^2, respectively, for both crops. In 1987, harvested areas were 7.20 m^2 and 3.60 m^2 for grain sorghum and soybeans, respectively. Yields were adjusted to constant moisture contents of 14 percent for grain sorghum and 12 percent for soybeans. Statistical analysis of yield data was performed using SAS analysis of variance procedure (SAS Institute, 1985) to detect significant differences between treatments.

Initial soil samples were taken in May 1986 from each plot to the depth of the underlying spoil using a truck-mounted Giddings press fitted with a 7.5 cm diameter Giddings probe (Manufacturer, Giddings Mach., Ft. Collins, CO). Two cores were taken for bulk density and two for chemical analysis from each plot for a total of 48 cores. In many instances rock fragments prevented the probe from penetrating into the spoil material, so that samples of spoil were not obtained with every soil core. For bulk density measurements, sections 7.5 cm in length were removed from each core for depths centered at 3.5, 11, and 26 cm for all plots and additional depths for deeper subsoil treatments of, 49, 75, and 105 cm. For chemical analysis, cores were divided into sections at 0-15, 15-30, 30-60, 60-90, and 90-120 cm, and spoil. Additional samples were taken with a hand probe for chemical and textural analysis at depths of 0-7.5 and 7.5-15 cm. Soil samples and spoil fines for chemical analysis were air-dried and ground to pass a 2 mm sieve. Soil pH was measured with a pH meter in a 1:1 soil/water suspension. Exchangeable cations were determined in ammonium acetate extracts with atomic absorption spectroscopy. The Bray-1 P method (Bray and Kurtz, 1945) was used as an index for available P. Values for electrical conductivity were determined from saturation extracts using procedures developed by the U.S. Salinity Laboratory Staff (1954). Organic matter was measured using the Walkley-Black procedure described by Nelson and Sommers (1986). Bulk densities were determined using a method described by Blake and Hartage (1986), using paraffin coated cores instead of clods. Particle size analysis was accomplished using the pipet method described by Gee and Bauder (1986).

An infiltration study was performed in August of 1986 using a double-ring infiltrometer described by Bertrand (1965). The infiltrometer consisted of an inner and outer ring measuring 35 cm and 60 cm in diameter, respectively. Ring installation was accomplished by placing a fitted steel plate over each ring and striking the center with a sledge hammer. In this way, the rings were driven into the soil evenly and with minimal disturbance. When installed, water was ponded over the infiltrometer and the rate of inflow was measured in the inner ring, using a hook gauge and a triangular engineer's scale. When steady state infiltration was reached measurements were taken every 30 minutes for three hours and used to calculate cumulative infiltration.

RESULTS AND DISCUSSION

Analyses of the initial soil samples established that there were no appreciable differences in soil properties between the plots for similar soil layers which might confound crop response to subsoil depth treatments. Aside from small differences which would not be expected to differentially impact plant growth, all soil depth treatments were quite similar for soil chemical and physical analysis. Selected soil properties for topsoil, subsoil, and spoil are averaged across all treatments and presented in Table 1. No growth limiting levels of nutrients were found that could not be corrected with proper fertilization, and topsoil pH was within a satisfactory range for the growth of crops used in the study. The spoil material is less desirable than the topsoil and subsoil because of the higher level of salin-

Table 1. Selected chemical and physical properties of the reconstructed soil.

Property	Topsoil		Subsoil		Spoil	
pH	6.6	(0.2)[a]	7.3	(0.2)	7.7	(0.2)
Exch. Cations:						
(cmol kg^{-1})						
Ca	15.2	(2.2)	22.7	(4.6)	24.0	(4.5)
Mg	5.5	(0.9)	7.3	(0.6)	4.9	(1.5)
K	0.5	(0.1)	0.6	(0.06)	0.5	(0.04)
Na	1.0	(0.3)	2.3	(0.3)	2.3	(1.1)
E.C., dS m^{-1}	0.8	(0.5)	2.8	(0.8)	4.4	(1.0)
Bray-P, mg kg^{-1}	5.8	(2.4)	1.9	(0.5)	1.8	(1.5)
O.M., %	1.7	(0.2)	0.7	(0.1)	1.1	(0.5)
Sand, %	15.9	(2.1)	15.0	(1.5)	20.4	(4.3)
Silt, %	42.3	(3.5)	34.6	(2.0)	34.5	(1.9)
Clay, %	41.8	(4.1)	50.4	(1.8)	45.1	(4.0)
B.D., g cm^{-3}	1.43	(0.08)	1.53	(0.06)	1.85	(0.15)

[a] Values are means averaged across all subsoil depth treatments; standard deviation of the mean is enclosed in parentheses.

ity (EC = 4.4 dS m^{-1}), but severe problems such as sodicity or acidity did not exist.

Soil textural analysis showed the topsoil to be a silty clay and the subsoil and spoil fines to be classified as clays. Bulk density data for the topsoil and subsoil were found to be at the high end of the reported range for similarly textured soils in the area (Penner, 1981). Visual observation of the replaced soil revealed an overall massive structure, particularly in the subsoil, a structural condition commonly observed in reconstructed soils that are heavily trafficked (McSweeney and Jansen, 1984). The massive structure and relatively high bulk density values suggest that the soils in this study were moderately compacted during reconstruction. Spoil bulk density, averaging 1.8 g cm^{-3}, was high and ranged from 1.65 to 2.25 g cm^{-3}. However, these values were not adjusted for the contribution made to bulk density from coarse fragments of shale and limestone. Visual observation of the spoil found it to be very hard and firmly packed. The physical condition of the spoil combined with its moderately high level of salinity suggest a poor medium for root growth.

Subsoil Replacement

A relatively wide range in growing season precipitation was encountered during the three years of the study (Fig. 1.). Precipitation was well above normal, near normal, and below normal for 1986, 1987, and 1988, respectively. Even with such diversity in precipitation, yields of both grain sorghum and soybeans were largely unaffected by subsoil replacement depth except for grain sorghum in 1988 (Table 2). In 1986, an abundant supply of moisture during all stages of plant growth and grain production contributed to the lack of response by both crops to increasing the depth of subsoil. Maximum yields of both crops were obtained with only 30 cm of topsoil over spoil. It is important to note that yields from all subsoil depth treatments were poor and that the "maximum yields" were low. The same observation applies to yields in 1987. The addition of subsoil under 30 cm of topsoil did not result in significantly higher yields of either crop, although there was a trend in that direction, particularly for soybeans. Unfortunately, grain sorghum response to subsoil depth was confounded by a severe infestation of corn earworm (Noctuidae, Peridroma saucia) that resulted in highly variable yields within subsoil depth treatments.

Climatic conditions in 1988 were the most stressful of the three years of the study with severe drought and high temperatures persisting throughout most of the growing season. The most severe moisture deficit occurred from mid-August through Mid-September which coincided with pod-set and seed development in soybeans. Moisture stress was so severe that soybean yields were equally poor on all subsoil depth treatments (Table 2). Although total precipitation was below normal, its distribution provided the grain sorghum favorable soil moisture conditions during head exertion and pollination. Moisture stress was most severe during grain filling. Under these conditions the effects of increasing the depth of the root zone on grain sorghum yields were apparent. Plants growing on 30 cm of topsoil without subsoil were visibly more stressed compared to plants on treatments with subsoil plus topsoil. The addition of 30 cm of subsoil under 30 cm of topsoil significantly increased yields over those on 30 cm of topsoil and 0 cm of subsoil. However, further increases in yield with subsoil depths of 60 cm and 90 cm were not

Figure 1. Monthly growing season precipitation for 1986-1988 at P & M Midway Mine site and 30 year average for Linn County.

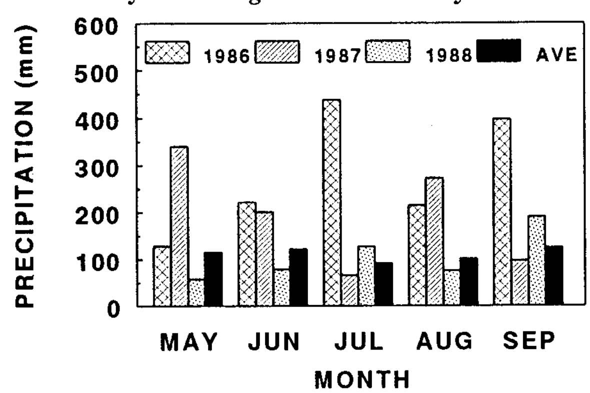

Table 2. Effects of subsoil replacement on rowcrop yields of reconstructed surface-mined soils in S.E. Kansas.

Year	Subsoil depth	GS-GS	SB-GS	Soybean
		--------Yield[a,b]--------		
1986	0	3515a	——	1746a
	30	3523a	——	1678a
	60	3393a	——	1765a
	90	3280a	——	1687a
1987	0	2294a	2517a	1600a
	30	1887a	2488a	1768a
	60	2346a	3124a	1916a
	90	3064a	3065a	1706a
1988	0	3350a	3639a	797a
	30	4735b	5355b	855a
	60	5248b	5554b	895a
	90	4873b	5314b	896a

[a] GS-GS = continuous grain sorghum, SB-GS = grain sorghum following soybeans.

[b] Means within each column and year followed by the same letters are not significantly different at P = 0.10.

significant at the 0.10 level of probability (Table 2). Yields from the 0 cm subsoil treatment averaged 71 and 68 percent of those from the 30 cm subsoil depth treatment for continuous grain sorghum and grain sorghum following soybeans, respectively. Similar yield reductions on an undisturbed soil were reported by Lewis et al. (1974) when grain sorghum was subjected to moisture stress at the same stage of growth. In this study, treatments with only 30 cm of topsoil over spoil were unable to supply sufficient moisture to grain sorghum under conditions of severe summer drought. Spoil material at this site is not a suitable medium to serve as the upper portion of the root zone.

Poor yields and lack of response to subsoil replacement of both crops in 1986 and 1987, and soybeans in 1988 suggest that these reconstructed soils are not in a condition that immediately support optimum levels of rowcrop production. This may be a consequence of using scraper pans during soil reconstruction creating soils that are compacted and poorly drained. Tillage and seedbed preparation was difficult, particularly in 1986, an abnormally wet year in which late planting and poor emergence undoubtedly contributed to low yields on all subsoil depth treatments. Soil settling may also have affected yields by altering surface topography and drainage, and forming depression areas in some plots. On the plots most severely affected by settling, yields were always lower than on plots where settling did not occur (data not shown).

The lack of response to subsoil replacement might also be a consequence of shallow rooting in the compacted subsoils. Measurements of soybean and grain sorghum rooting depth were not made, but shallow rooting by fescue was observed in a separate study at this site (Caldwell, 1989). Fescue root counts made at incremental depths on treatments with 30 cm of topsoil and either 0 or 30 cm of subsoil showed an abrupt decrease in root numbers immediately below the replaced soil material (data not shown). Few roots were found to penetrate more than a few centimeters into the spoil. Where either 60 or 90 cm of subsoil was replaced, few roots were found below the 60 cm depth even though total soil depths (topsoil plus subsoil) were 90 cm and 120 cm, respectively. Based upon grain sorghum yield response to replaced subsoil depth in 1988, it appears that the depth of root penetration may have been similarly restricted in previous years. This is supported by the findings of Jansen et al. (1984). They attributed poor corn and soybean yields on reconstructed soils to increased soil strength from compaction by scraper pans. Root growth was restricted in the dense subsoil, and replacing soil materials to depths greater than the maximum depth of rooting had no beneficial effect on yield.

Ripping

Ripping to a 51 cm depth at the time of soil reconstruction resulted in significant increases in yield of soybeans but not grain sorghum in 1986 (Table 3). Generally, favorable effects of ripping on soybean yield have been attributed to increasing the accessibility of stored subsoil moisture and nutrients to plant roots (Kamprath et al.., 1979; Martin et al.., 1979). In this study, however, prolonged periods of water-logged and ponded soil conditions were evident on all treatments as a result of the abnormally high amounts of precipitation received at the site in 1986. Because these soils were moderately compacted, the ripping operation likely resulted in a lowering of bulk density (Oussible and Crookston, 1987; Barnhisel et al., 1988) and increased total porosity (Oussible and Crookston, 1987) in the zone affected by the ripper shanks. Such physical alterations of the reconstructed soil would result in improved drainage of the upper portion of the soil

Figure 2. Effects of ripping on water infiltration into the newly reconstructed soils.

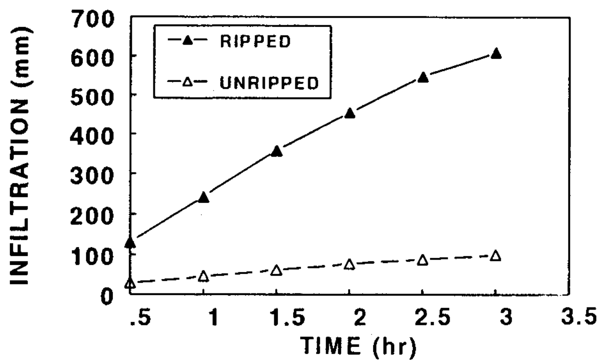

Table 3. Effects of ripping newly reconstructed surface mined soils on rowcrop yields in S.E. Kansas.

		Yield[a,b]		
Year	Treatment	GS-GS	SB-GS	Soybean
		kg ha^{-1}		
1986	Unripped	3296	——	1475
	Ripped	3560	——	1963*
1987	Unripped	2436	2679	1680
	Ripped	2360	2917	1816
1988	Unripped	4383	4886	774
	Ripped	4724*	5045	946

*,** Significant at P=.05 and P=.01, respectively.

[a] GS-GS = continuous grain sorghum, SB-GS = grain sorghum following soybeans, averaged across all subsoil depth treatments.

[b] Unless otherwise indicated means are not significantly different at P = 0.10.

profiles as is indicated by the infiltration data given in figure 2. Because soybean is especially sensitive to the poorly aerated conditions of excessively wet soils (Coop. Ext. Serv., Kans. St. Univ., 1987, C-449) it appears that the response to ripping was due to increasing the effective volume of soil favorable for the growth and function of soybean roots.

Favorable effects of ripping were again expressed as increased yields of continuous grain sorghum in 1988, the third crop year after ripping was performed. Powell et al.. (1985) reported similar ripping effects in Kentucky which they also attributed to increased moisture availability. They also noted that ripping effects were still apparent after four years. Yields of grain sorghum following soybeans showed a similar, but less pronounced trend in 1988 that was not statistically significant. Even though the ripping treatment clearly resulted in increased grain sorghum yields in 1988, the magnitude of the increase was relatively small and yields were still poor. In addition, the depth of ripping (51 cm) corresponded closely to the depth of replaced soil (topsoil plus subsoil) where the yield response to replaced soil depth ended. This suggests that if the depth of ripping were increased to affect the deeper subsoil depth treatments, yields of grain sorghum might also be increased.

CONCLUSIONS

Rowcrop yields at this site did not significantly respond to subsoil replacement except in the third year for grain sorghum. When moisture deficit conditions occurred in 1988, the benefits of subsoil replacement of at least 30 cm resulted in significant yield increases of grain sorghum over that grown on 30 cm of topsoil alone. The influence of climatic conditions, particularly precipitation, on crop response to replaced soil depth has been demonstrated in other studies as well (Merrill et al., 1985; Jansen et. al, 1984). On reclaimed soils where no growth limiting soil chemical properties exist, the moisture supplying capacity of reconstructed soils may be the most important parameter in the achievement of optimum crop yields. At this site, the moisture supplying capacity of the subsoil has likely been reduced from excessive compaction during soil reconstruction. Yields of grain sorghum and soybeans on all subsoil depth treatments at this site were generally low in each year of the study. This was due in part to poor soil physical conditions, shallow rooting, and differential soil settling of the newly constructed soils. Under these conditions, there is no benefit to replacing more than 30 cm of subsoil plus 30 cm of topsoil because shallow rooting of rowcrops will limit the yield benefit of building deeper soils.

The reconstructed soils at this site may have the potential to produce higher rowcrop yields than were obtained in this study. Ripping to a 51 cm depth during soil reconstruction enhanced the soil's ability to support rowcrop yields, particularly when precipitation was limiting crop growth. The results suggest that ripping to a depth that affects the deeper subsoils might be one way to increase rowcrop yields of these reconstructed soils. Additional studies will be required to determine if the deeper reconstructed soils at this site could be more fully exploited, possibly by deeper ripping treatments, so that greater productivity could be demonstrated at this site. This will require operations that can be employed to reduce or eliminate the negative effects of compaction that result when deeper soils are replaced.

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The Effects of Deep Tillage of Reclaimed Mine Soils on Corn Root Development

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Abstract. Reclamation following surface mining of coal often results in severe soil compaction. Deep soil loosening may be effective in alleviating this problem. The objectives of this study were to evaluate the effects of deep tillage on corn (Zea Mays L.) yield, rooting depth and proliferation as well as resulting changes in soil physical properties. Different depths of deep tillage (20, 40, 60, 80 cm) were employed on surface mined land at a site in Perry County, IL using Kaelble-Gmeinder TLG subsoilers. The research site consisted of four replications of a two-factor experiment, these being tillage depth and annual management. Root sample cores were obtained from each treatment to a depth of 80 cm using a Giddings probe. The sample cores were cut into 20 cm increments and the roots were separated from the soil using a hydropneumatic elutriation system. The root samples were stained and then measured using an Agvision Image Analysis system. Root length density was determined for all treatments in 20 cm depth increments. The 0-20 cm increment was not measured due to the amount of plant debris and other foreign material. Significant root length density increases were observed in the deeper collected soil cores from the plots that were deep tilled (80 cm). This deeper rooting also resulted in increased corn yields. Bulk density samples obtained using the Giddings probe revealed a reduction in bulk density at the deeper depths as tillage depth increased. Soil strength measurements taken with a constant velocity recording cone penetrometer indicated that penetrometer resistance was also lowered at the deeper soil depths with increasing depths of tillage.

INTRODUCTION

Illinois has the largest known reserves of bituminous coal of any state in the nation (Smith and Stall, 1975). It has been estimated that the total coal reserves in Illinois exceed 180 billion tons and underlie 65 percent of the state (Personeau, 1983). About 13 percent of these coal reserves are obtainable through surface mining techniques (Fehrenbacher et al., 1977). A portion of these strippable reserves are overlain by some of the most productive soils in the state. For the past several years, 1,600 to 2,400 hectares (3,950 to 5,930 acres) per year have been surface mined in Illinois (Indorante et al., 1981). Public law 95-87, the Surface Mining Control and Reclamation Act (SMCRA) of 1977, introduced many new controls on the coal industry. One of these was the requirement to reestablish equivalent (premining vs. postmining) crop productivity. Illinois contains approximately 8.5 million hectares (21 million acres) of prime farmland with an estimated 198,000 hectares (490,000 acres) underlain by strippable coal reserves (Illinois Department of Mines and Minerals, IDMM 1985). This reclamation law has had a significant impact on restoring crop productivity on reclaimed lands.

Acceptable plant rooting media is generally considered to be replaced topsoil over a replaced B-C horizon. Severe soil compaction associated with material placement has been identified as one of the major limiting factors in achieving postmining productivity for reclaimed mine soils in Illinois. The degree and depth of compaction in mine soils varies with the reclamation practices used in reconstruction (Vance et al., 1987).

Since the passing of SMCRA, there has been an increased concern with improving the rooting environment in reclaimed soils. One method under investigation is the disruption of the soil by the use of deep tillage techniques. Alleviation of soil compaction is not always easy to achieve. Success depends on site and soil conditions and how the land is managed following the initiation of crop production.

Best management strategies following reclamation remain unclear. Some deep loosening of the restored soil may be necessary if the level of crop productivity that meets the requirement for bond release is to be achieved (Hooks et al., 1987). The type of deep tillage necessary for loosening, as well as the depth and frequency of loosening, remain largely unanswered. In addition, the most appropriate land management for augmented soils after loosening is unknown.

The objectives of this research were to evaluate the effects of differing depths of deep tillage of surface mined farmland on the following: (1) the soil physical properties, (2) corn (Zea mays L.) root development and proliferation, and (3) corn growth and productivity.

METHODS AND MATERIALS

Site Description

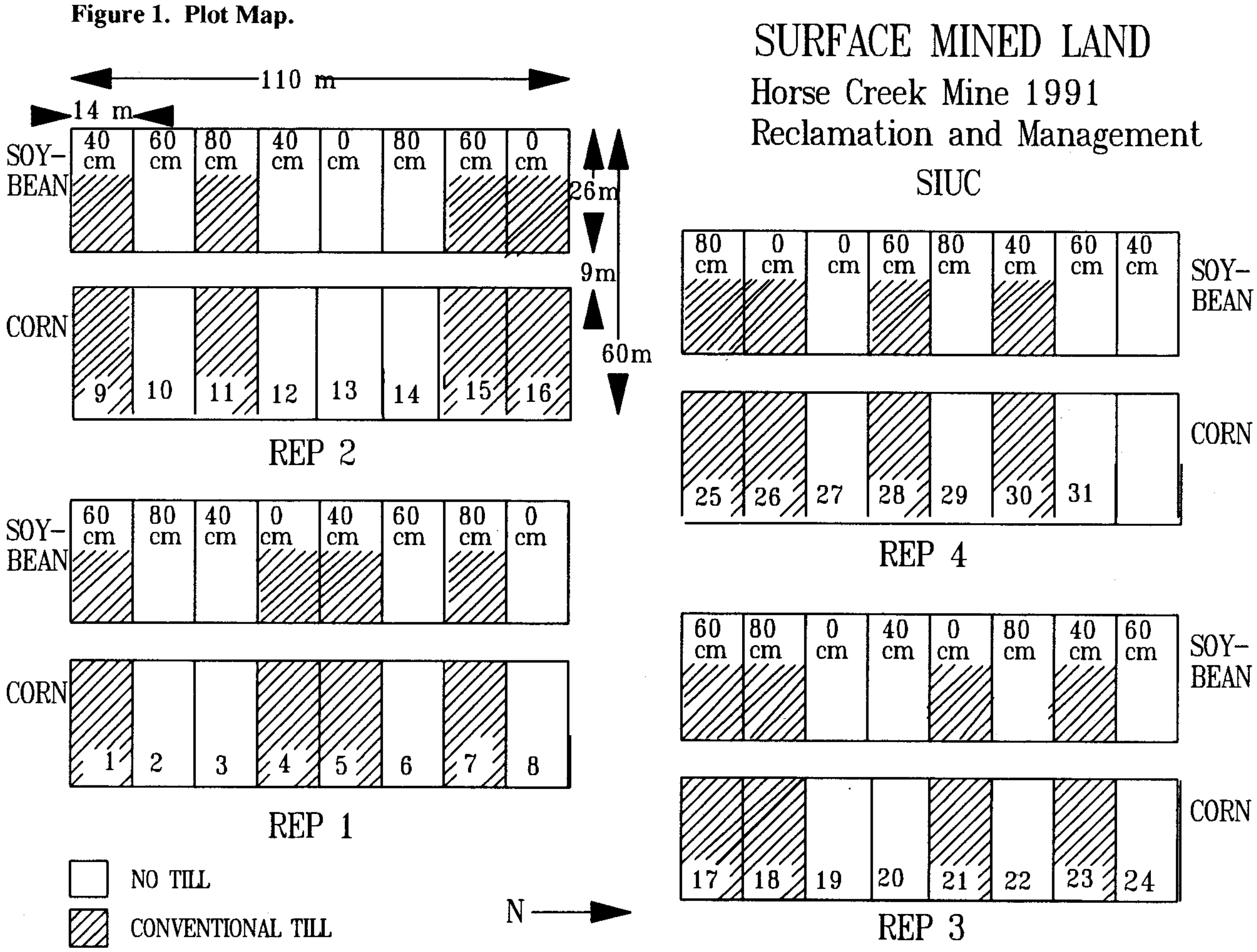
The experimental site is located at the Arch of Illinois Inc., Horse Creek Mine near Conant, in Perry County, Illinois. Prior to mining, the soils at the study area were classified as a Stoy and Weir silt loam series and the Hoyleton-Darmstadt and Cisne - Huey silt loam associations (Grantham and Indorante, 1988). These soils have been re-classified as Schuline series after reconstruction. The research site was constructed with mixed B and C horizon soil material placed to a depth of at least 122 cm (48 in) using the cross-pit bucketwheel excavation system. The rooting material was placed on top of spoil debris and subsequently leveled by bulldozer. Topsoil was replaced by scrapers to cover the B-C mix to a depth of 20 cm (8 in) and leveled to final grade. Following completion of the reclamation work, the area was seeded to a forage grass/legume mixture in the fall of 1987.

Four replications (blocks) of a two-factor experiment (tillage depth and management practice) were established at the reclaimed site. Each block measured 61 by 100 m (200 by 360 ft) and was divided into eight plots, each measuring 14 by 61 m (45 by 200 ft) (figure 1). Blocks 1 and 2 were located on the backslope of an initial wheel spoil pile with a slope of approximately 5%. Blocks 3 and 4 were located on an adjacent nearly level to gently sloping portion of the site.

Preliminary Soil Assessments

During the fall of 1988, prior to deep tillage, twelve pits were excavated at the research site for profile

Figure 1. Plot Map.



characterization. These pits were dug with a backhoe and were located in the turnstrips along the plot borders. At this time, soil samples for mechanical analysis, bulk density, and percent moisture determinations were collected. Measurements of topsoil thickness were also made along with photographic documentation.

Surface soil samples were collected in August 1988. Composite soil samples were taken in 20 cm (8 in) increments to a depth of 80 cm (32 in) from each plot. The major chemical properties analyzed were soil pH, extractable phosphorus (P), exchangeable potassium (K), and organic matter content. Soil pH was potentiometrically determined by using a 1:1 soil-water paste method (McLean, 1982). Bray P1, extractable P, and exchangeable K were analyzed using methods described by Olsen and Sommers (1982) and Knudson et al. (1982), respectively. Soil organic matter content was measured using a modified Walkley-Black procedure described by Nelson and Sommers (1982).

Plot Management Prior to Deep Tillage

Wheat (Triticum aestivum L.) was broadcast on the site in the fall of 1988 to serve as a cover crop. Fertilizer was applied August 26, 1988 as a dry fertilizer mixture of 0-46-0, 18-46-0, and 0-0-60. The rates applied were 67 kg ha^{-1} (60 lb/ac) of N, 360 kg ha^{-1} (320 lb/ac) of $P_2 0_5$, and 400 kg ha^{-1} (360 lb/ac) of $K_2 0$. In May of 1989, herbicides were applied at the research site to provide for weed control and to kill the existing cover. On May 12, 1989, the corn hybrid variety FS 8475 was no-till planted on the study site. The planting rate was 56,800 seed per hectare (23,000 seed per acre). Nitrogen was applied to the plots at a rate of 190 kg ha^{-1} (170 lb/ac) as a 28% urea-ammonium nitrate solution. Soil strength measurements were taken on May 30 and 31, 1989, using a constant velocity recording cone penetrometer (Hooks and Jansen, 1986).

Companion soil samples were obtained at the same time to determine the soil moisture content. On July 25, 1989, bulk density samples were collected from the plots using a tractor mounted Giddings probe.

In early August of 1989, the corn was harvested as silage in order to initiate deep tillage treatments on the site. Silage samples were collected prior to harvest in order to assess within plot variability. Eight subplots were harvested from each plot.

Deep Tillage Treatments

On August 17, 1989, deep tillage treatments were initiated at the research site. The implements used for the deep tillage were the Kaelble-Gmeinder model TLG-12 and TLG-460 subsoilers. These machines utilize a vibrating shank and foot to cut and lift to various depths to 80 cm (32 in). Four tillage treatments (20, 40, 60, and 80 cm or 8, 16, 24, and 32 in respectively) were implemented. The TLG-12 was used to perform the loosening for the 60 cm (24 in) and 80 cm (32 in) treatments while the TLG-460 was used to rip the 40 cm (16 in) treated plots. The control plots received no deep tillage but were chisel plowed to a depth of about 20 cm (8 in) using a conventional agricultural chisel plow. Each treatment was randomized to occur twice within each block. A cover crop of rye (Secale cereale L.) was seeded in October for erosion control.

Plot Preparation 1990

On April 23, 1990, the plots were sprayed with an early preplant mixture of glyphosate (Roundup), atrazine (4L), and metolachlor (Dual) at the rates of 0.7, 0.9, and 0.5 liters per hectare, respectively, to kill the rye cover crop and provide weed control during the growing season.

Due to excessive rainfall following herbicide application and continuing through May and early June, (Table 1) corn planting was delayed until June 19, 1990. On that date, the hybrid variety FS 6933 was planted at a rate of 55,600 seed per hectare (22,500 seed per acre) using a Kinze four row no-till planter. Due to wet soil conditions, the conventional tillage management system was not applied. The remaining 40% of the herbicide was applied on the date of planting along with nitrogen at a rate of 224 kg ha^{-1} (200 lb/ac) as a 28% urea-ammonium nitrate solution.

Soil Physical Property Evaluations 1990

On July 18 and 19, 1990, soil strength measurements were obtained at the site. Each plot was divided into eight subplots and one measurement was taken per subplot using a constant velocity recording cone penetrometer. Each measurement was taken to a depth of 125 cm (50 in). The timed logging of data was recorded on a Campbell CR10 data acquisition system attached to the penetrometer. The data was later transferred to a computer disc and analyzed to determine soil strength at

Table 1. Rainfall Distribution (cm) at Horse Creek Mine, Conant, IL (May through September, 1990 and 1991).

	Rainfall (cm)				
	May	June	July	August	September
1990	21.0	10.7	6.7	6.2	16.9
1991	6.9	3.1	7.3	2.3	18.0
Normal*	9.6	9.5	9.5	7.9	7.0

*Normal rainfall based on 30-year precipitation data, NWS, DuQuoin, IL.

various depths throughout the soil profile. Companion soil moisture samples were obtained on the same day soil strength measurements were taken. Soil moisture was determined using the gravimetric method.

On August 31, 1990, soil cores were collected at the site to be used for bulk density determinations. The cores were obtained using a Giddings probe coring machine. The bulk density cores were cut into 20 cm (8 in) increments to a depth of 80 cm (32 in). These segments were oven dried and weighed to determine oven dry mass for bulk density calculation.

Root Measurements

On August 30, 1990, soil cores were taken at the site to determine the corn root length density. The cores were taken to a depth of 100 cm (40 in). Two cores were obtained from each plot. The intact soil cores were placed on monolith trays and wrapped in plastic before being transported to the laboratory and placed in cold storage. The cores were cut into 20 cm (8 in) increments in the lab, placed in a dispersing agent (sodium hexametaphosphate) and soaked for 12 to 24 hours before separation of the soil and roots. The roots were separated from the soil using a hydropnuematic elutriation system designed after one built by Smucker et al. (1982). Following separation from the soil, the roots were placed in jars containing a 10% ethyl alcohol solution and stored in the dark at room temperature until root measurements were made.

In order to obtain root length, the roots were first placed in a solution of methyl violet dye for 48 hours before being measured. The instrument used to determine root length was an Agvision Image Analysis System. This system was designed specifically for root measurements, leaf area measurements, and object counts. To calculate root length density, the length of each sample was divided by the volume of soil from which the roots were extracted.

Plant Parameter Measurements

On August 24, 1989, corn tissue samples were obtained from each plot for plant nutrient analysis. Twenty leaves were collected at random from each plot. Each leaf collected was located opposite and just below the ear of the plant. The samples were then oven-dried, ground, placed in labeled bags, and sent to a commercial laboratory for complete nutrient analyses.

On October 15, 1989, pre-harvest plant parameter measurements were taken on the plots. These measurements included plant populations, plant and ear heights, percent of barren stalks, and lodging incidence. On October 29, 1990, eight subplots, corresponding to penetrometer locations from earlier in the year, were hand harvested from each plot. The harvest samples were transported to the Southern Illinois University Agronomy Research Center in Carbondale where the grain was shelled from the ears, weighed, and analyzed for moisture content. Yields were adjusted to 15.5% moisture content.

1991 Field Work

On May 8, 1991, the plots that were randomized to receive conventional tillage management were disked in preparation for planting. At the same time, a 9 m (30 ft) wide turnstrip was installed through the middle of each block in order to divide the plots and introduce crop rotation as a management tool (figure 1). On May 28, 1991, corn and soybeans (Glycine max L.) were planted at the site. Corn hybrid variety FS 6933 was planted at a rate of 57,000 seeds per hectare on all treatments. Lorsban insecticide was placed in the furrow at the time of planting. Nitrogen fertilizer was applied at a rate of 224 Kg N/hectare as a 28% urea-ammonium nitrate solution along with the corn herbicide Lariat. The soybean cultivar planted was FS Hisoy Variety HS 462 at the rate of 395,000 seeds per hectare. Only the data relating to the corn studies will be included in this report. Both corn and soybeans were planted at 76 cm (30 in) row widths. Squadron herbicide was applied to the soybeans the same day as planting and gramoxone was used as a contact herbicide on the no-till plots. Shortly after planting, neutron probe access tubes were installed on the experimental site to determine soil moisture changes throughout the growing season. Soil strength measurements were also obtained during June using the constant velocity recording cone penetrometer. Soil moisture samples were obtained at the same time. Soil cores for bulk density and root length density determinations were collected in early September using methods consistent with those obtained the previous year.

Plant parameter measurements were obtained during 1991 using the same methods that were used in 1990. These measurements included leaf nutrient analysis, plant populations, plant and ear heights, percent of barren stalks, lodging incidence, and grain yield.

RESULTS AND DISCUSSION

Preliminary Soil Assessments

The soil pits excavated in August of 1988 revealed an average of 33 cm (13 in) of topsoil over a typically massive subsoil. The depth of topsoil ranged from 20 cm (8 in) to 55 cm (22 in). Granular structure dominated the topsoil, while some platey structure and subangular blocky characteristics appeared to have resulted from traffic associated with soil reconstruction.

Soil samples obtained in August of 1988 indicated that the surface soil (0-20 cm) had a pH which was neutral in reaction. The rooting medium (below 20 cm) had a pH which was neutral to slightly alkaline in reaction (Table 2). The trend of soil pH increasing with depth is not clearly understood. The mixing of the soil materials that occurred with the bucket-wheel excavation method should have resulted in a rather uniform matrix of material with depth. If the material was worked in lifts, such as with panscraper placed material, or confined (block by block for example), these differences could be attributed to material handling.

Soil test levels of plant available phosphorus (P) and potassium (K) were quite uniform within the surface 80 cm of soil but were "low" in terms of amounts required for optimum crop growth. Soil test levels in the "plow layer" (0-20 cm) should be 50 and 300 kg ha^{-1} of P and K respectively, for ideal crop production on agricultural soils. The soil tests revealed that the level of plant available P ranged from 15 to 19 kg ha^{-1} while the available K ranged from 165 to 181 kg ha^{-1} (Table 3). As a consequence, P and K fertilizers were applied at rates of 160 and 370 kg ha^{-1}, respectively, prior to the initiation of deep tillage.

The soil organic matter (O.M.) decreased with depth (Table 2). The surface soil (0-20 cm) had an O.M. content of 1.03%, typical of the topsoil of most agricultural soils of the region. The 0.75% O.M. content found at the 20-40 cm depth is probably due to the average topsoil depth of 33 cm (13 in). The uniformly low O.M. contents in the 40-60 and 60-80 cm increments (0.41 and 0.33%) were typical of those found in the B and C horizons of Southern Illinois soils.

Soil Physical Properties Assessment

Tables 3 and 5 give the average penetrometer resistance and soil bulk density respectively, of the reclaimed soils on the Horse Creek mine experimental site prior to the initiation of deep tillage treatments. High traffic during the reclamation process probably resulted in the severe compaction of the reclaimed soil. The average bulk density for the surface soil was 1.47 g/cm^3 which increased to 1.82 g/cm^3 in the 60-80 cm increment. The average penetrometer readings between 20 to 60 cm were all much higher than 2.0 MPa (290 psi). It was reported (Taylor and Gardner, 1963; Taylor and Burnett, 1964) that penetrometer resistance values greater than 2.0 MPa (290 psi) may result in severe root impedance, and if it reaches 2.6 MPa (380 psi), root elongation will be nearly impossible. The average soil depth to encounter a mean penetrometer reading of 2.0 MPa was less than 15 cm.

Table 3 shows the soil strength values obtained for each treatment before tillage (1989) and two years after the tillage treatments were implemented (1991). Table 4 gives the soil moisture content at the time penetrometer readings were obtained. These results indicate that a reduction in soil strength was achieved as a result of deep tillage. No significant reductions were observed in the control treatments. The plots that were tilled to a depth of 40 cm had lower soil strength values following tillage to a depth of 40 cm. The 60 cm tilled plots also had significant reductions in soil strength to the depth that tillage occurred. The results from the 80 cm tillage treatments indicated that the deepest depth of tillage had the most significant reductions in soil strength. Lower soil strength readings were evident to the depth that the plots were tilled. These results indicate that the deeper tillage depths were the most beneficial in reducing soil strength throughout the rooting zone.

Bulk density results obtained before tillage (1989) and following tillage (1990) are shown in Table 5. These values show that bulk density was reduced in the plots that received the deeper tillage treatments. The control treatments remained virtually unchanged from

Table 2. Soil Fertility Variability in Increments to 80 cm Prior to Deep Tillage at Horse Creek Mine, Conant, IL (1989).

	Soil Chemical Properties			
Depth	pH	P	K	Organic Matter
- cm -		---- kg ha^{-1} ----		---- % ----
0-20	7.0 d*	17 b	176 a	1.03 a
20-40	7.2 c	19 a	165 b	0.74 b
40-60	7.5 b	18 ab	168 b	0.41 c
60-80	7.8 a	15 c	181 a	0.33 c

*Values followed by the same letter in the same column are not significantly different at the 5% level.

Table 3. Penetrometer Resistance (psi) at Horse Creek Mine, Conant, IL (1989 and 1991).

		Tillage Treatment		
Depth(cm)	Control	40 cm	60 cm	80 cm
		1989 (Before Tillage)		
0-20	231 a*	228 a	219 a	226 a
20-40	505 a	509 a	536 a	479 a
40-60	440 a	464 a	429 a	469 a
60-80	323 a	355 a	317 a	345 a
80-100	263 a	301 a	206 a	264 a
		1991 (2 years After Tillage)		
0-20	274 a	216 b	205 bc	180 c
20-40	460 a	319 b	196 c	173 c
40-60	386 a	419 a	229 b	169 b
60-80	320 a	361 a	334 a	234 b
80-100	252 a	307 a	285 a	265 a

*Values followed by the same letter in the same row are not significantly different at the 5% level.

1989 to 1990. The results from the plots that were tilled to 40 cm revealed that bulk density had been reduced to the depth of tillage. The plots that received the 60 cm tillage treatment had a significant reduction in bulk density at the 20-40 cm depth. The 40-60 and 60-80 cm depths also indicated a lower bulk density following tillage, although not as great as the 20-40 cm depth. The 80 cm tillage treatments appeared to have the greatest reduction in bulk density following deep tillage. There were significant differences found at the 20-40, 40-60, and 60-80 cm depths when comparing 1989 and 1990 bulk density results. These results would indicate that, as with soil strength, bulk density may also be reduced by the use of deep tillage. The deeper depths of tillage appear to be the most beneficial in reducing bulk density to the desired depths.

Corn Root Development Assessments

The results from the corn root length measurements obtained during 1990 and 1991 are shown in Table 6. The results of these studies show an increase in root length density at deeper soil depths with increasing tillage depth. In 1990 there was not a significant difference found in the 20-40 cm zone, but below this depth significant differences were observed. At the 40-60 cm depth the 80 cm treatments had an average root length density of 0.458 cm/cc and the 60 cm treatments averaged 0.44 cm/cc. These values were significantly higher than those obtained from the 40 cm and control treatments which were 0.262 and 0.256 cm/cc respectively. At the 60-80 cm depth the 80 cm tilled plots had a significantly greater root length density (0.195 cm/cc) than the 60 cm treatments (0.056 cm/cc), the 40 cm treatments (0.035 cm/cc) and the control treatments (0.015 cm/cc). The 80 and 60 cm treatments also had a significantly greater total root length density than the 40 cm and control treatments.

The 1991 root length measurements also revealed greater root length densities at deeper soil depths with increasing tillage depth. The 80 cm tillage treatments had significantly greater root length densities (0.419 cm/cc) at the 40-60 cm depth than the 60 cm treatments (0.263 cm/cc), the 40 cm treatments (0.189 cm/cc) and the control treatments (0.154 cm/cc). The same was also true for the 60-80 cm depth. The 80 cm tilled plots had an average root length density of 0.208 cm/cc, which was significantly greater than the 60 cm treatments (0.040 cm/cc), the 40 cm treatments (0.029 cm/cc) and the control treatments (0.033 cm/cc). The 80 cm tilled treatment was the only one that had roots in the 80-100 cm depth. Significant differences were also found with relation to total root length density. The 80 cm treatments had an average total root length density of 1.118 cm/cc compared to 0.855 cm/cc for the 60 cm treatments, 0.721 cm/cc for the 40 cm treatment, and 0.592 cm/cc for the control treatments. This data shows that corn root length density can be increased by deep tillage to the depth of tillage. This increased rooting capability also resulted in increased yields.

Table 4. Soil Moisture Content (%) When Penetrometer Readings were Obtained at Horse Creek Mine, Conant, IL (1989 and 1991).

		Tillage Treatment		
Depth(cm)	Control	40 cm	60 cm	80 cm
		1989		
0-20	15.6 a*	17.7 a	16.7 a	15.0 a
20-40	17.6 a	18.1 a	17.5 a	16.7 a
40-60	19.6 a	19.3 a	18.9 a	18.4 a
60-80	19.8 b	20.7 ab	22.3 a	21.1 ab
		1991		
0-20	14.3 a	14.8 a	15.5 a	15.7 a
20-40	16.1 b	18.1 a	18.2 a	18.4 a
40-60	16.3 b	17.7 b	18.9 a	19.7 a
60-80	17.1 b	17.6 b	17.9 b	19.6 a

*Values followed by the same letter in the same row are not significantly different at the 5% level.

Table 5. Soil Bulk Density (g/cc) at Horse Creek Mine, Conant, IL (1989 and 1990).

		Tillage Treatment		
Depth (cm)	Control	40 cm	60 cm	80 cm
		1989 (Before Tillage)		
20-40	1.66 a*	1.69 a	1.63 a	1.66 a
40-60	1.80 ab	1.74 ab	1.71 b	1.83 a
60-80	1.80 a	1.75 a	1.82 a	1.78 a
		1991 (After Tillage)		
20-40	1.67 a	1.50 b	1.47 b	1.49 b
40-60	1.80 a	1.76 ab	1.67 b	1.55 c
60-80	1.83 a	1.84 a	1.76 b	1.68 c

*Values followed by the same letter in the same row are not significantly different at the 5% level.

Table 6. Corn Root Length Density (cm/cc) at Horse Creek Mine, Conant, IL (1990-1991).

		Tillage Treatment		
Depth (cm)	Control	40 cm	60 cm	80 cm
		1990		
20-40	0.916 a*	0.938 a	0.807 a	0.752 a
40-60	0.256 b	0.262 b	0.440 a	0.458 a
60-80	0.015 b	0.035 b	0.056 b	0.195 a
Sum	1.197 b	1.225 b	1.303 a	1.405 a
		1991		
20-40	0.405 b	0.503 ab	0.552 a	0.440 ab
40-60	0.154 b	0.189 b	0.263 ab	0.419 a
60-80	0.033 b	0.029 b	0.040 b	0.208 a
80-100	0.00 b	0.00 b	0.00 b	0.051a
Sum	0.592 c	0.721 bc	0.855 b	1.118 a

*Values followed by the same letter in the same row are not significantly different at the 5% level.

Corn Grain Yields

Table 7 shows the average corn grain yield for each tillage treatment in 1990 and 1991. In 1990 excessive rainfall during May and early June delayed corn planting until June 19. Despite the late planting date and subsequent below normal rainfall, significant differences in yield were found among the various treatments. The 80 cm tillage treatments had an average yield of 4,650 kg ha^{-1} (69 bushels per acre), significantly higher than the 60 cm tillage treatments which yielded 3,000 kg ha^{-1} (45 bushels per acre). The 40 cm and control treatments had average yields of 2,400 and 1,350 kg ha^{-1} (36 and 20 bushels per acre), respectively.

In 1991 below normal rainfall throughout the growing season proved to be disastrous to the development of corn at this site. However, significant differences in yield were observed. The 80 cm tillage treatments had an average yield of 2,150 kg ha^{-1} (34 bushels per acre), which was significantly higher than the 60 cm tilled plots 650 kg ha^{-1} (10 bushels per acre), the 40 cm tilled plots (125 kg ha^{-1}) (2 bushels per acre) and the control plots which had no harvestable ears and yielded 0 kg ha^{-1} (0 bushels per acre). This data would indicate that the deeper depths of tillage were the most beneficial for increasing corn grain yields.

CONCLUSIONS

Soil profile examination showed that mined soil reclaimed by the cross-pit bucketwheel excavation system with topsoil replacement at the Horse Creek mine resulted in a massive structure subsoil. Soil fertility assessment indicated that the surface soil pH was nearly ideal for corn production. However, the available P and K of the reclaimed mined soil were both low. Soil organic matter content decreased with depth. The reclaimed subsurface soil at the Horse Creek mine has a very high bulk density and penetrometer resistance. This compaction is severe enough that mechanical soil augmentation is required for proper growth of most crops. Soil bulk density and penetrometer resistance can be reduced by deep tillage. The depth at which tillage is performed and soil moisture conditions at the time of tillage determine the amount and the depth to which these properties are affected. Root length density is enhanced at deeper soil depths by deep tillage. Soil rooting volume can be expanded to the depth that tillage occurs.

Bulk density and soil strength are good predictors of root system performance in newly constructed soils. Corn plant growth can be enhanced using deep tillage on compacted reclaimed surface mine soils. Corn grain yields may also be increased using deep tillage on reclaimed surface mined land. The deeper tillage depths used in this study appear to be the most beneficial for increasing corn yields. However, due to abnormal weather conditions during 1990 and 1991, further studies at this site will be needed in determining the effects of deep tillage on corn yield over a wider range of climatic conditions. The yield responses that may be achieved in a season with more normal rainfall patterns has yet to be determined.

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Table 7. Corn Grain Yield (kg ha^{-1}) at the Horse Creek Mine, Conant, IL (1990 and 1991).

	Control		40 cm		60 cm		80 cm	
1990	1350 c*	(20)+	2400 bc	(36)	3000 b	(45)	4650 a	(69)
1991	0 c	(0)	125 c	(2)	650 b	(10)	2150 a	(34)
MEAN	675 c	(10)	1260 bc	(19)	1825 b	(28)	3400 a	(52)

* Values followed by the same letter in the same row are not significantly different at the 5% level.

+ Values in parenthesis are bushels per acre.

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Effects of Deep Tillage on Surface Mined Land in Southern Illinois

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Abstract. The effects of six deep tillage treatments ranging in depth from 9 to 42 inches applied to a reconstructed surface mine soil were evaluated over a four year period in southern Illinois. The mine soil consisted of 9 inches of scraper-placed topsoil over 48 inches of scraper-placed rooting media. The pre-tillage physical condition of this mine soil is described as compact and massive. A nearby tract of Cisne silt loam (fine, montmorillonitic, mesic Mollic Albaqualf) was used as an unmined comparison. Significant differences in corn and soybean yield, soil strength, and net water extraction were observed among tillage treatments. Depth of tillage needed on the mine soil to achieve productivity comparable to permit target yields were found to be affected by initial levels of soil compaction.

INTRODUCTION

Poor soil physical condition has proven to be the most severe and difficult limiting factor in the reclamation of many prime farmland soils (Dunker et al., 1991). Newly constructed soils commonly lack a continuous macropore network necessary for water movement, aeration, and root system extension. Also, plant root growth is often severely inhibited by excessively high soil strength (Thompson, et al., 1987; Meyer, 1983).

There are two sources of the physical condition problem in man-made soils. One is the use of severely compacted, high strength soil materials from great depth. If this is not adequately disrupted the soil may maintain high strength. Secondly, and more commonly, is compaction induced by earth moving equipment in the process of moving and placing the soil material.

There is a belief that the physical condition problem can be solved by simply growing forage legumes. These have been assumed to help when included in the crop rotation, or after an initial cropping period with continuous forage legumes. We have completed two experiments over the last ten years to evaluate their efficacy in solving this problem. The practice, though having some merit, has proven inadequate. Soil strengths are commonly just too high to allow diffuse distribution of even alfalfa root systems. The roots tend to form mats in desiccation cracks and leave much of the soil volume largely unaffected. Physical improvement is slow and inadequate. Perhaps that should not be surprising, as severely compacted glacial till layers in some natural soils have also remained intact, even after one or two centuries of agriculture. Forage legumes would likely be much more effective in soil improvement if soil construction procedures could be modified so as to reduce the severity of the soil compaction.

It has also been advocated that the problem can be solved by limiting the moving of soil materials to periods when they are dry. This approach has some merit, but is also inadequate. First is the reality that the mines simply do not have that option. Second is the experience that, even though moving materials dry does help substantially, the finished product still has excessive soil strength and bulk density. Research should continue to be directed towards finding soil construction methods which will prevent the problem, but meanwhile, means for amelioration of deeply compacted soils must be investigated.

Because of the need for deep soils in the heart of the corn belt, compaction is particularly serious and the solution is particularly difficult. Natural soils of the Midwest are commonly 60 inches deep. The predominate crops can effectively exploit soils of that depth. The rainfall is adequate to completely recharge a 60 inches soil in most years. In addition, periods of drought stress during the growing season are sufficiently common as to require maximum available water storage capacity in soils for maximum yields.

There are many tillage options which have been proven effective to 12-15 inches depth for ameliorating wheel traffic effects of farm machinery on undisturbed soils. Some methods are being used effectively to 30 inch depth on mine soils. A deep ripper, the Kaeble

Gmeinder TLG-12, which has an effective depth of 32 inches has been successful in lowering soil strength of a graded cross-pit wheel spoil in western Illinois (Dunker, et al., 1989). Corn yields from the TLG-12 treatment averaged over a two year period for both a topsoil replaced and wheel spoil treatment were significantly higher than the non-tilled treatment. Also they were not significantly different to corn yields produced on a nearby undisturbed Sable silty clay loam (fine-silty, mixed, mesic Typic Haplaquoll). Methods for effective physical improvement to depths beyond 36 inches in reclaimed farmland soils remain unproven.

Objective

Determine the effectiveness of deep soil tillage methods for improving soils with poor physical condition.

MATERIALS AND METHODS

The Site

The site for this experiment is at the Consolidation Coal Company Burning Star #2 mine located near Pinckneyville in Perry County, Illinois. Prime agricultural soils disturbed by surface mining for coal in this area primarily belong to the Stoy, Hosmer, and Cisne soil series. Stoy soils (fine-silty, mixed, mesic Aquic Hapludalf) are nearly level and gently sloping and are somewhat poorly drained. Hosmer soils (fine-silty, mixed, mesic Typic Fragiudalf) are gently sloping and sloping and are moderately well drained. Cisne soils (fine, montmorillonitic, mesic Mollic Albaqualf) are nearly level or depressional and are poorly drained. Soils of this region are formed on 4 to 6 feet of Peorian loess overlying Illinoian glacial till. Most of these soils have highly weathered acidic subsoils which are high in clay, highly plastic, and poorly aerated when wet. These subsoils tend to be only slowly permeable and, when dry, restrictive to root penetration. The C horizon consists of calcareous loess and calcareous glacial till and is chemically suitable for supporting plant growth.

The mine soil at this site was constructed in 1983 using a scraper-haul system to replace 40 inches of rooting media and 8 inches of topsoil. Texture of rooting materials ranged from silt loam to clay loam, but clay content never exceeded 30%. Physical characteristics of this mine soil can best be described as compact and massive. Preliminary soil samples were taken to determine levels of soil fertility. Required amounts of inorganic fertilizer and limestone were applied prior to the application of deep tillage treatments.

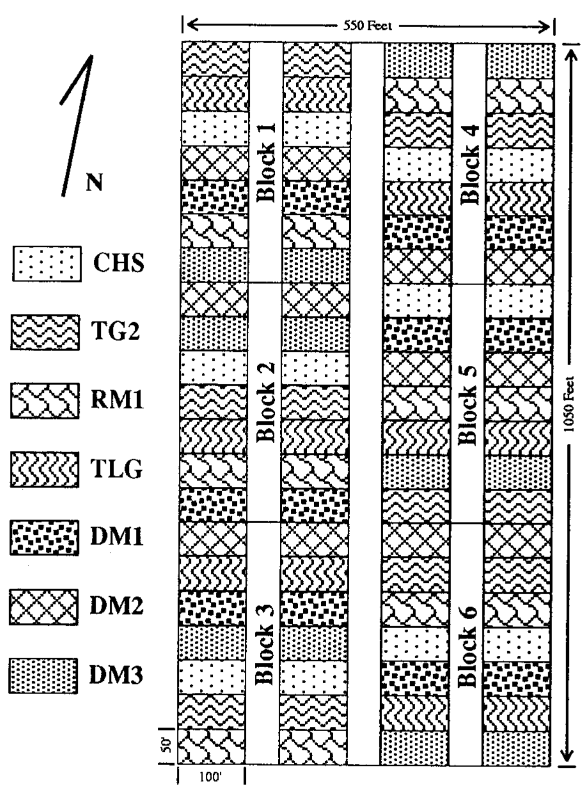
Experimental Design and Layout

A randomized complete block experimental design providing for six replications of seven treatments was prepared for the site (Figure 1). The plots were surveyed and staked out in April, 1987. Experimental plots have two rows of three blocks each, aligned in roughly a north-south direction. Each of the 42 plots is 50 feet wide and 250 feet long, to provide two 50 feet by 100 feet subplots for corn and soybeans, respectively, separated by a 50 feet turn strip.

Pre-treatment Evaluation of Soil Strength

A deep-profile penetrometer (Hooks and Jansen, 1986) was used to measure soil strength to a depth of 44 inches prior to the application of tillage treatments (Table 1). Soil strength was highly variable, but the pattern did not compromise the experiment. Analysis of this pre-tillage penetrometer data revealed that while there was no soil strength difference across blocks, there were significant differences in soil strength among blocks. Soil strength levels of the west three blocks are significantly higher (0.05 level) than soil strength levels of the three east blocks for each depth segment of the soil profile.

Figure 1. Deep Tillage Plots at Burning Star #2.



The difference in soil strength between the east and west sides is apparently due to two factors. First, there was a time difference in grading. There was a one year delay in grading of the cast overburden, between the east and west sides, but all of the root medium and topsoil materials were placed during the June-August period of 1983. Secondly, aerial photography from early June, 1983 indicates a scraper haul road along the west side of the site.

Application of the Deep Tillage Treatments

The plot areas at the site were sprayed in early August, 1987 with one quart of Roundup and 1 pint of 2,4-D per acre to kill the dense, foot-tall stand of the initial crop of legumes. This was done to reduce the amount of plugging with green trash during tillage and to reduce control problems in the row crops to be planted in 1988.

Five of the tillage treatments were completed during the next month (Table 2). Those treatments are:

TLG Kaelble Gmeinder TLG-12. The TLG uses a cut-lift operation to shatter the soil to a depth of about 36 inches. A wide, moving foot is attached to each of the three shanks to cut and lift the soil as the machine moves forward.

RM1 RM1 Processor by Harry Jones. The RM1 Processor has four curved, vibrating shanks cut from 1.5 in steel. The shanks do not have expanded points or wings. Two hydraulic vibrators are used; each operating two of the four shanks. It has an effective tillage depth of about 36 inches.

DM1 DMI Deep Ripper (prototype). This machine is a two-lift, solid shank ripper. Two "Turbo" chisel shanks are used to fracture the soil to an 18 inch depth ahead of the main shank. The main shank is cut from 4 inch steel. It is parabolic and has a winged point, 32 inches wide with a 7 inch lift. The point of the main shank is designed to run 50 inches deep. The machine incorporates a hydraulic trip/reset mechanism to prevent breakage. Successive passes are separated by 48 inches. Under favorable moisture/tilth conditions the floor of the tilled zone shears nearly horizontally, yielding a minimum tilled depth of 48 inches. Moisture content at that depth was a bit high at the time of treatment, and a pronounced ridge of unloosened material was left between shank passes.

TG2 Tiger II chisel by DMI, Inc. This is a commercially available chisel used in commercial agriculture for tillage in the 12-18 inch depth range. It is not really considered adequate for the needed loosening in reclaimed soils because of its depth limitations. It was included for comparison, to see just what could be accomplished with a conventional machine of this type.

CHS Standard agricultural chisel plow with an effective depth of 9-10 inches. This treatment is considered the tillage control treatment.

The DM1 Deep Ripper and the RM1 processor treatments were disced prior to tillage to reduce plugging of trash. The Tiger II and the TLG were equipped with coulters to eliminate this problem. Immediately after tillage, each plot was leveled with a disc. The RM1 processor was used to rip the turn strips and border areas after all of the treatments had been applied to allow for drainage from plot areas to avoid a "bathtub" effect.

An additional deep tillage treatment was applied to the experiment in August, 1988 utilizing one of the two blank treatments designed into the experiment. This treatment, the DMI Super Tiger (DM2), is similar to the DM1 prototype previously used. It does, however, have a redesigned point design and requires a larger power unit (Caterpillar D10) for more consistent depth and greater ground speed.

A final tillage treatment was applied in early September, 1990 utilizing the last of the blank treatments in the experimental design. This new treatment (DM3) is the DMI Tiger with a modified center shank. The DMI

Table 1. 1987 penetrometer values before tillage at Burning Star #2.

Treatment	Seg 2 9-18"	Seg 3 18-27"	Seg 4 27-36"	Seg 5 36-44"
	- - - - Soil Depth - - - -			
	- - - - Penetrometer Resistance, PSI - - - -			
1	332.5 a[1/]	369.9 a	327.9 a	260.6 c
2	365.7 a	420.0 a	350.4 a	319.9 ab
3	358.6 a	391.8 a	335.5 a	314.2 ab
4	336.5 a	391.9 a	352.4 a	327.2 a
5	348.1 a	411.2 a	338.2 a	283.6 bc
6	316.0 a	386.3 a	350.5 a	322.3 ab
7	353.0 a	396.9 a	307.4 a	301.3 abc
LSD (0.05)	59.9	61.9	62.5	41.2

[1/] Values followed by the same letter within a segment are not significantly different at the 0.05 level.

Table 2. Tillage equipment description.

Treatment	Power Unit	Horsepower	Tillage Width	Depth of Tillage
CHS	Ford 6600	85	72"	9"
TG2	Case	230	150"	14"
RM1	John Deere 850 B	180	120"	32"
TLG	John Deere 850 B	180	90"	32"
DM1	Caterpillar D8LSA	440	48"	48"
DM2	Caterpillar D10	530	48"	48"
DM3	Caterpillar Challenger 65	235	28-32"	38"

Tiger tool is normally a three-point mounted, three shank plow with shanks and points of the DMI Tiger II design (12-14 inch effective depth). The center shank was replaced with a larger, retractable shank of similar design. Once the tillage tool is in the soil at about 18 inch depth, the large center shank is hydraulically forced down to effectively work at 38-40 inch depth and width of tillage passes at 40 inches. This is a single, parabolic shank static ripper.

Tillage treatments were applied to plot areas only once, except for fall tillage in which the chisel plow is applied across all treatments. Consequently, both initial tillage effectiveness and longevity of tillage effects can be evaluated.

A nearby tract of Cisne silt loam (Mollic Albaqualf) was used as an unmined comparison. Management factors for the mined and unmined soils are the same and similar to practices followed by a typical farming operation in the area (Table 3). Corn (*Zea mays L.*) and soybeans [*Glycine max* (L) Merr] are rotated each year within the experimental design. A minimum tillage management system was used to minimize traffic and recompaction on the plots. Soil moisture is monitored during the growing season using a neutron probe.

Grain yield samples for corn were harvested after black-layer formation indicated physiological maturity and soybeans were harvested when all pods were brown. Grain yield estimates were based on the amount of shelled grain after adjusting for variation in moisture content of grain to 15.5 % for corn and 12.5 % for soybeans.

RESULTS AND DISCUSSION

Effects of Deep Tillage on Soil Strength

Soil strength measurements using the deep-profile penetrometer were taken prior to planting in 1988, 1989, and 1991 to evaluate tillage effects. Analysis of these data are presented in Table 4. Soil strength measurements taken in April, 1991, indicate that tillage effects remain consistent to initial post-tillage soil strengths 42 months after application of tillage treatments. In summary, using the chisel treatment (CHS) as the control treatment, the Tiger II (TG2) was successful in lowering soil strength down to Segment 2 (9-18"). The TLG and RM1 significantly lowered soil strength to Segment 3 (18-27) and was numerically lower than the CHS or TG2 in Segment 4 (27-36"). Both the DM1 and DM2 deep plows were successful in significantly lowering soil strength to the 44 inch depth. First year measurements of the DM3 treatment show it had similar effects to the RM1 and TLG treatments.

It is important to note that even though the magnitude of soil strength values are different for 1988, 1989, and 1991 results, the significant groupings of treatments are essentially the same for all years. This is probably due to differences in soil moisture content at the time data was collected. Figure 2 shows graphically the effects of tillage on soil strength over the entire soil profile to a depth of 45 inches in 1989. The plotted curves data reveal that the effective tillage depth of each treatment is representative of the designed depth of

Table 3. Plot management record for BS#2 experiment.

	1988	1989	1990	1991
		Corn:		
Hybrid	FR27xMo17 LH119xLH51	FR27xMo17 LH119xLH51	LH119xLH51	LH119xLH51
Planting date	May 11	May 11	June 19	May 28
Planting rate	23,200 /acre	24,200 /acre	24,200/acre	24,200/acre
Fertilizer	170 lb/a P 260 lb/a K 200 lb/a N	80 lb/a P 190 lb/a K 200 lb/a N	80 lb/a P 300 lb/a K 200 lb/a N	100 lb/a P 180 lb/a K 200 lb/a N
Herbicide	4 lb Extrazine 2 qt Lasso	2.5 lb Extrazine 1 qt Lasso	1 qt Aatrex 4L 1 qt Dual 1 qt 2,4-D EPP/28%	1 qt Aatrex 4L 1 qt Dual
Insecticide	Furadan 15G	Lorsban 15G	Lorsban 15G	Lorsban 15G
		Soybeans:		
Variety	Williams 82 Union	Williams 82 Union	Union	Union
Planting date	May 12	May 11	July 2	May 29
Planting rate	72 lb/a	62 lb/a	62 lb/a	62 lb/a
Fertilizer	170 lb/a P 260 lb/a K	80 lb/a P 190 lb/a K	80 lb/a P 300 lb/a K	100 lb/a P 180 lb/a K
Herbicide	2 pt Prowl 2/3 pt Sceptor	2 pt Prowl 2/3 pt Sceptor	2 qt Roundup 1 qt 2,4-D EPP	1 qt Prowl 2/3 pt Scepter

Figure 2. 1989 Burning Star #2 Penetrometer Profiles

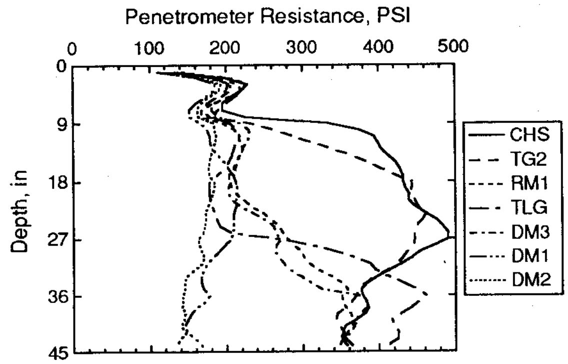


Table 4. Penetrometer data from BS#2 plots after tillage.

Treatment	Seg 2 9-18"	Seg 3 18-27"	Seg 4 27-36"	Seg 5 36-44"
	Soil Depth			
	Penetrometer Resistance, PSI			
		1988		
Spare B[1/]	804.1 a[2/]	603.6 a	417.1 a	446.4 a
Spare C	768.8 a	584.4 a	415.8 a	432.8 ab
CHS	712.8 a	554.6 a	405.9 ab	434.5 ab
TG2	568.7 b	582.3 a	416.4 a	379.0 b
DM1	235.9 c	193.6 b	180.7 c	210.6 c
RM1	218.7 c	266.7 b	345.0 b	387.9 ab
TLG	193.4 c	219.1 b	338.9 b	390.2 ab
LSD (0.05)	99.5	123.9	67.1	61.5
		1989		
Spare B	521.9 a	515.8 a	419.7 a	381.6 a
CHS	457.4 ab	433.4 a	374.5 ab	350.5 a
TG2	400.4 b	457.7 a	394.5 ab	350.6 a
RM1	200.1 c	195.3 b	320.9 b	346.3 a
TLG	192.0 c	181.3 b	323.5 b	388.5 a
DM1	188.9 c	160.2 b	148.0 c	176.4 b
DM2	151.8 c	179.5 b	173.2 c	138.3 b
LSD (0.05)	71.0	135.6	87.3	62.9
		1991		
CHS	402.5 a	459.5 a	423.6 a	369.4 a
TG2	343.6 b	448.9 a	411.0 ab	349.9 a
DM3	218.8 c	231.4 b	290.6 c	370.3 a
RM1	210.4 c	240.2 b	320.0 bc	355.2 a
TLG	203.7 c	189.5 b	382.8 abc	427.0 a
DM1	188.9 c	211.0 b	179.4 d	159.6 b
DM2	181.1 c	175.1 b	156.5 d	140.2 b
LSD (0.05)	56.3	109.0	96.3	91.6

[1/] Soil treatments are: Spare, untilled plot held in reserve for future application; CHS, conventional chisel plow, 8" tillage depth; TG2, DMI Tiger II Colter, 16" depth; RM1, Harry Jones RM1 soil processor, 32" depth; TLG, Kaeble-Gmeinder TLG ripper, 32" depth; DM1, DMI deep plow (first design prototype, 48" depth; DM2, DMI deep plow (second design), 48" depth; DM3, DMI deep plow, 38" depth.

[2/] Values followed by the same letter within a segment are not significantly different at the 0.05 level.

tillage for each piece of tillage equipment. These soil strength curves represent the average curve across the six replications of each treatment. The pronounced high strength peak on the soil strength curve for the conventional chisel plow (CHS) is probably due to traffic induced compaction by scrapers from the topsoil replacement operation. The Tiger II (TG2) treatment has successfully eliminated this effect but the soil strength of the TG2 and CHS treatments remain high throughout the soil profile. Soil strength profiles of the RM1 and TLG are similar to the DMI deep plow treatments to a depth of about 30 inches. Below this depth soil strength increases with depth until resistance levels are comparable to the TG2 and CHS treatments. Both the DM1 and DM2 deep plow (48 in effective depth) show relatively low soil strength throughout the soil profile.

Rowcrop Yields

Tillage treatments significantly influenced corn and soybean yields in all years (Table 5). Corn hybrids were not a significant factor in either 1988 or 1989 when two hybrids were used as a split treatment. There was a soybean varietal response in 1988 but not in 1989. Significant block differences have occurred for both corn and soybeans. In general, the three blocks on the west side of the experiment (Blocks 1-3) yielded lower than the three blocks on the east side (Blocks 4-6).

Grain yields from 1988 through 1991 growing seasons are presented in Table 6. The DMI deep plow treatments produced corn yields significantly higher than any of the other mine soil tillage treatments in all of the four years studied. The TLG and RM1 corn yields were comparable in every year while the Tiger II (TG2) and conventional chisel (CHS) treatments yielded the lowest in three of the four years. Corn yields for the first year on the DMI Super Tiger deep plow (DM2) treatment were significantly higher than any of the other tillage treatments in 1989, and were comparable to those obtained on the nearby tract of undisturbed Cisne soil in both years it has been included as a treatment. Penetrometer data indicates that soil strength levels for the DM1 and DM2 treatments are similar.

The first year advantage of the DM2 treatment may be due to increased water storage over the fall and winter. Early 1989 season neutron probe data show that the DM2 had significantly higher volumetric water content in the 3-5ft depths than the DM1. 1990 and 1991 corn yields of the DM1 and DM2 were not significantly different at the 0.05 level of significance. Both of these deep plow treatments produced corn yields comparable to corn yields on the undisturbed Cisne soil in 1990. No significant difference among the CHS, TG2, RM1, and TLG treatments occurred in the

Table 5. Mean squares and level of significance for the various effects in the analysis of variance for yield.

Source of Variation	d f	Mean Square			
		Corn			
		1988	**1989**	**1990**	**1991[1/]**
Tillage Trt (T)	5,6	16113.25**	17023.79**	3078.34**	3933.94**
Block (B)	5	1519.83**	882.40**	12442.07**	476.4+
Error (a)	25,30	316.45	119.75	199.05	222.67
Hybrid (H)	1	81.53	248.34		
H x B	5	178.55*	200.23		
H x T	5	124.81	154.30		
Error (b)	25,30	64.69	99.17		
		Soybeans			
Tillage Trt (T)	5,6	141.50**	586.66**		
Block (B)	5	10.64*	290.58**		
Error (a)	25,30	6.67	26.97		
Variety (V)	1	31.82**	13.67		
V x B	5	2.42	1.04		
V x T	5	3.33	2.44		
Error (b)	25,30	2.90	3.31		

[1/] Only one corn hybrid and soybean variety was planted in 1990. Soybeans were not harvested in 1990 or 1991 due to severe weather and unestimable harvest loss.
**· Statistically significant at the 0.01 level.
*· Statistically significant at the 0.05 level.

Table 6. Mean yields for BS#2 deep tillage treatments and Cisne soil.

Soil treatment	1988	1989	1990[3/]	1991	88-91 Mean	89-91 Mean
	Yield, bu/a					
	Corn					
CHS[1/]	37.5 e[2/]	60.9 d	70.1 b	7.5 c	42.5 d	44.7 d
TG2	42.7 de	52.5 d	85.1 b	5.6 c	44.8 d	45.5 d
RM1	55.6 cd	86.0 c	79.4 b	21.9 b	59.9 c	61.5 c
TLG	67.7 c	83.3 c	76.3 b	22.3 b	61.8 c	59.7 c
DM3				30.4 b		
DM1	87.3 b	126.7 b	112.6 a	66.9 a	97.8 b	101.5 b
DM2		142.6 a	124.1 a	57.0 a		106.9 ab
Cisne	135.7 a	141.6 a	130.3 a	68.3 a	118.5 a	112.5 a
Target Yield-HCL[4/]	95.6	95.6	95.6	95.6	95.6	95.6
Adjusted Target	68.6	83.3	84.0			
	Soybeans					
CHS	13.6 b	13.2 c	[3/]	[3/]	13.4 b	
TG2	12.5 b	14.2 c			13.3 b	
RM1	13.7 b	13.9 c			13.8 b	
TLG	14.2 b	14.2 c			14.2 b	
DM3						
DM1	21.1 a	24.3 b			22.7 a	
DM2		30.2 a				
Cisne	18.7 a	23.7 b			21.2 a	
Target Yield-HCL[4/]	31.1	31.1			31.1	
Adjusted Target	23.2	22.7			22.9	

[1/] Soil treatments are: CHS, conventional chisel plow, 8" tillage depth; TG2, DMI Tiger II Colter, 16" depth; RM1, Harry Jones RM1 soil processor, 32" depth; TLG, Kaeble-Gmeinder TLG ripper, 32" depth; DM1, DMI deep plow (first design prototype), 48" depth; DM2, DMI deep plow (second design), 48" depth; DM3, DMI deep plow, 38" depth; Cisne, undisturbed Cisne soil..
[2/] Yields followed by the same letter within a crop are not significantly different at the 0.05 level.
[3/] Soybeans were not harvested in 1990 and 1991 due to excessive water damage .
[4/] Base target yields of high capability lands (HCL) for BS#2 permit area calculated by IL Dept. of Agric . This base target yield is adjusted annually by a county success factor to adjust for weather variation.

1990 growing season. The DMI deep plow treatments (DM1, DM2) exceeded target corn yield levels in 1988, 1989, and 1990. TLG mean yields were comparable to the target yields in 1989. 1988 yields for the TLG were only 1 bu/a less than target. Target level yields for soybeans were achieved only in 1989 by the DMI Deep plow treatments (DM1, DM2).

Soybean yields for the DMI deep plow treatments were significantly higher than the other mine soil tillage treatments in both 1988 and 1989 and were comparable to those obtained on the Cisne soil. No yield differences occurred on the other tillage treatments in either year. Soybean yields were poor in both 1988 and 1989 at this location due to adverse weather effects. Rainfall from August to mid-September was substantially below normal in both 1988 and 1989. Soybeans planted in 1990 and 1991 were not harvested due to: i) extreme weather stress during pod-fill stage, and ii) excessive late season rainfall in both 1990 and 1991 resulting in unestimatible treatment-specific harvest loss. The lateness of soybean planting delayed maturity until after considerable rainfall had been received. Saturated soil conditions coupled with the low strength soils resulting from deep tillage prevented support of harvest machinery on these plots without causing significant damage and recompaction of tillage treatments.

Measurement of agronomic variables for corn (Table 7) show significant 1988-91 mean differences among tillage treatments for % barren plants, shelling percentage (ratio of shelled grain per total ear weight), average ear weight, and test weight (a measure of grain density). Corn planted on the DMI deep plow treatments (DM1, DM2) produced a significantly lower percentage of barren plants, greater average ear weight, and grain with significantly higher test weights than the other tillage treatments.

Significant differences in yields of the experimental blocks have occurred. Blocks 1-3 on the west side have yielded lower than blocks 4-6 on the east side. Pre-tillage evaluation with the cone penetrometer showed significant initial differences in soil strength between the east and west sides of the plots (Fig. 3). Soil strength levels of the west side were significantly greater than the east blocks for each depth segment. Post-tillage penetrometer data shows similar trends (Fig. 4). Note that the relationship of soil strength and tillage depth is

Figure 3. Comparison of pre-tillage soil strength of west blocks(1-3) and east blocks(4-6).

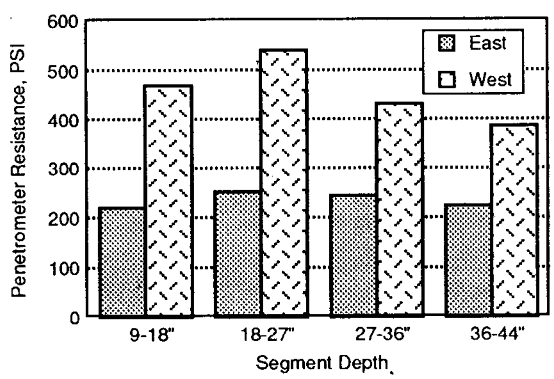


Figure 4. Comparison of tillage treatments on 9-44" ave soil strength of west blocks(1-3) and east blocks(4-6).

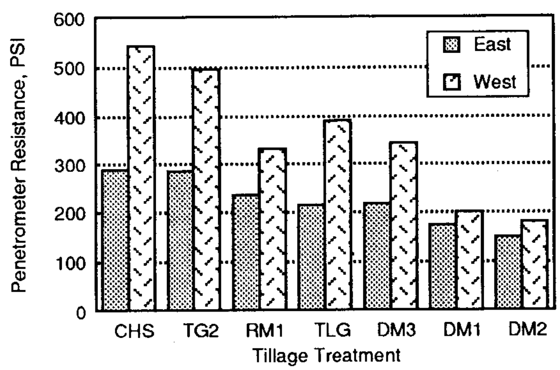


Table 7. 1988-91 mean values for measured agronomic variables for corn.

Soil treatment	1988-91 Mean			
	% Barren Plants	Shelling %	Ave. Ear Wt	Test Wt
CHS[1/]	26.1 a[2/]	82.7 a	.278 c	58.0 c
TG2	24.1 ab	79.0 b	.286 c	58.4 b
RM1	14.9 bcd	82.8 a	.293 c	57.9 c
TLG	17.6 abc	79.6 b	.312 c	57.7 c
DM1	10.4 cd	84.9 a	.414 b	59.0 ab
DM2	8.5 cd	84.9 a	.455 a	59.0 a
Cisne	7.3 d	83.8 a	.437 ab	57.3 c

[1/] Soil treatments are: CHS, conventional chisel plow, 8" tillage depth; TG2, DMI Tiger II Colter, 16" depth; RM1, Harry Jones RM1 soil processor, 32" depth; TLG, Kaeble-Gmeinder TLG ripper, 32" depth; DM1, DMI deep plow (first design prototype), 48" depth; DM2, DMI deep plow (second design), 48" depth; Cisne, undisturbed Cisne soil..

[2/] Values followed by the same letter within a variable are not significantly different at the 0.05 level.

consistent on both sides. Reduction of soil strength with increasing tillage depth is occurring at the same rate, only the magnitude of soil strength is different. This data suggests that the effect of tillage in reducing soil strength levels is affected by initial levels of compaction. The practical application of this finding is that compaction is better prevented than cured.

Yields of corn and soybeans comparing the east and west sides within and across years show that significant yield differences have been observed within treatments (Table 8 and Table 9). Mean corn and soybean yields of the west (blocks 1-3) and east (blocks 4-6) sides have been significantly different for each year and when averaged across years. This data suggests that the initial level of compaction, i.e. soil strength, will affect the depth of tillage needed to achieve productivity. Three year mean corn yields of the TLG and RM1 on the lower soil strength east side blocks are comparable to the adjusted target yield values for the permit area, while the corn yields on the higher soil strength west blocks are several bushels lower. Only the DMI deep plow treatments produced two and three year mean yields comparable to base and adjusted target yields on the west side. Soybean yields for all tillage treatments on the west blocks were significantly lower than those obtained on the east blocks. However, soybean yields of the DMI deep plow treatments on both the east and west blocks were comparable to the permit area target yields.

Soil test results (Table 10) indicate that while differences in the levels of elements exist, these nutrients are at high enough levels to not be yield limiting.

Table 8. Corn yields of blocks 1-3 (west side) and blocks 4-6 (east side).

Blocks	CHS	DM2	DM1	RM1	TG2	TLG	DM3	Mean
	Yield, bu/a							
				1988				
East (4-6)	48.2 a[1/]	-	91.9 a	65.6 a	47.5 a	77.0 a		66.0 a
West (1-3)	25.8 b	-	82.2 a	45.6 b	37.8 a	58.4 b		50.0 b
				1989				
East (4-6)	58.4 a	142.9 a	128.4 a	92.7 a	61.0 a	93.5 a		96.2 a
West (1-3)	63.3 a	142.3 a	125.1 a	79.4 b	44.1 b	73.1 b		87.9 b
				1990				
East (4-6)	102.2 a	154.3 a	137.4 a	106.1 a	104.7 a	109.7 a		119.1 a
West (1-3)	21.9 b	78.8 b	75.4 b	39.4 b	55.5 b	26.1 b		49.5 b
				1991				
East (4-6)	7.8 a	60.2 a	71.9 a	32.2 a	7.5 a	28.3 a	42.3 a	34.8 a
West (1-3)	7.2 a	53.8 a	61.8 a	11.5 b	3.8 a	16.0 a	18.4 b	25.6 a
				1988-91 Mean				
East (4-6)	53.8 a	123.2 a	108.3 a	75.8 a	54.8 a	73.6 a		79.2 a
West (1-3)	35.6 b	108.6 b	93.3 b	50.7 b	36.1 b	58.9 b		61.1 b

[1/] Yield values followed by the same letter within a tillage treatment and year are not significantly different at the 0.05 level.

Table 9. Soybean yields of blocks 1-3 (west side) and blocks 4-6 (east side).

Blocks	CHS	DM2	DM1	RM1	TG2	TLG	DM3	Mean
	Yield, bu/a							
				1988				
East (4-6)	14.2 a[1/]	-	20.5 a	14.6 a	13.4 a	15.4 a		15.6 a
West (1-3	13.1 a	-	21.7 a	12.7 b	11.7 a	12.9 b		14.4 b
				1989				
East (4-6)	17.8 a	34.9 a	31.4 a	18.4 a	16.4 a	18.4 a		22.9 a
West (1-3)	8.7 b	25.5 b	17.3 b	9.4 b	9.7 b	10.0 b		13.4 b
				1988-89 Mean				
East (4-6)	16.0 a	34.9 a	25.9 a	16.5 a	15.0 a	16.9 a		19.6 a
West (1-3)	10.9 b	25.5 b	19.5 b	11.1 b	10.7 b	11.5 b		13.9 b

[1/] Yield values followed by the same letter within a tillage treatment and year are not significantly different at the 0.05 level.

Analysis of leaf composition of corn and soybean leaves from a companion study at this site confirms that nutritional factors are not a problem. It is concluded that soil physical condition is the most probable limiting factor in achieving productivity of these soils.

Soil Moisture

Neutron access tubes were installed at the Burning Star #2 site for the 1988 and 1989 growing seasons. One access tube was installed in each corn plot of the six replications of each tillage treatment. Six tubes were also installed in the nearby undisturbed Cisne soil. Density data was collected in late August of each year by using a Gamma probe in the access tubes. This gamma density data is summarized in Table 11. These gamma density values appear high because the Gamma probe is sensitive to both soil and volumetric water content. In summary, gamma density of the TLG and RM1 are numerically lower than the Chisel treatment in the 2-3 ft depth. The DMI treatments and the Cisne soil have significantly lower gamma densities at the 3-5 ft depths.

The net water extraction from June to August is summarized in Table 12. This net water extraction does not take into account any recharge that took place during this period. This data shows that corn extracted the most water from the Cisne and DMI deep plow treatments in the 3-5 ft depths in both 1988 and 1989. The chisel and Tiger II treatments extracted little water from these depths. The TLG and RM1 treatments released more water than the CHS and TG2 treatments at the 2-3 ft depths, with extraction tapering off below 3 feet.

The water extraction trends of the tillage treatments tend to follow the same trends found in the yield

Table 10. Soil test means for soil treatments at the Burning Star #2 Experiment,(east vs west blocks).

Side	Depth	pH	CEC	P	Ca	Mg	K	Na	S	B	Fe	Mn	Cu	Zn
				-----------	lbs/acre	-----------			---------	Parts per	Million	---------		
East	0-8"	7.3 a[1/]	10.1 a	60 b	2629 a	627 a	188 a	88 a	30 b	.51 a	187 a	138 b	1.49 a	2.06 a
West	0-8"	7.3 a	10.1 a	69 a	2727 a	535 b	199 a	82 a	38 a	.48 a	177 a	156 a	1.30 a	1.86 a
East	8-16"	7.1 b	13.1 b	35 a	2938 b	1081 a	96 b	239 a	69 a	.47 a	160 a	131 b	1.45 a	1.63 a
West	8-16"	7.4 a	16.4 a	37 a	4460 a	937 a	120 a	158 b	66 a	.48 a	148 a	176 a	1.39 a	1.82 a
East	16-24"	6.9 b	22.7 a	28 a	4454 b	1840 a	259 a	397 a	93 a	.41 b	153 a	150 b	1.80 a	1.43 a
West	16-24"	7.9 a	24.0 a	19 b	6602 a	1445 b	227 b	167 b	57 b	.46 a	112 b	184 a	1.40 b	1.28 b

[1/] Values followed by the same letter within an element and depth are not significantly different at the 0.05 level.

Table 11. 1988-89 Burning Star #2 Gamma Density.

			Depth, ft		
TRT	1	2	3	4	5
	----------------------	----------------------	gamma density	----------------------	----------------------
			1988		
CHS[1/]	1.290 ab	1.979 a	2.051 ab	2.025 a	2.053 ab
TG2	1.270 ab	1.903 ab	2.093 a	2.054 a	2.016 ab
RM1	1.257 ab	1.713 c	2.020 abc	2.097	2.061 ab
TLG	1.418 a	1.787 bc	1.900 bcd	2.107 a	2.092 a
DM1	1.140 b	1.753 bc	1.851 d	1.840 b	2.014 b
CIS	1.205 ab	1.641 c	1.872 cd	1.814 b	1.993 b
LSD(0.05)		0.218	0.180	0.168	0.119
			1989		
CHS	1.697 a	1.925 a	2.028 a	2.073 a	2.070 ab
TG2	1.659 ab	1.869 ab	2.012 a	2.079 a	2.079 ab
RM1	1.644 abc	1.726 c	1.986 ab	2.063 a	2.085 a
TLG	1.706 a	1.882 a	1.966 ab	2.064 a	2.078 ab
DM1	1.534 bcd	1.777 bc	1.832 c	1.878 b	2.056 b
DM2	1.508 cd	1.759 c	1.790 c	1.846 b	2.060 b
CIS	1.478 d	1.755 c	1.864 bc	1.847 b	1.990 c
LSD(0.05)	0.143	0.096	0.133	0.076	0.024

[1/] Values followed by the same letter within an element and depth are not significantly different at the 0.05 level.

and penetrometer data. The poorest extraction came from the shallow tillage and the deeper the tillage the greater the water extraction. Two year mean water extraction values plotted with two year mean corn yields in Figure 5 show this relationship.

SUMMARY

Data from this study support the following general conclusions:

1. Tillage treatments significantly affected crop yields, soil strength levels, net water extracted by growing crops, and measured agronomic variables such as % barren plants, shelling %, average ear weight, and average test weight of grain. 9-44 inch average soil strength decreased with increasing tillage depth.

2. Corn yield increased with increasing tillage depth within and across years. Weather variables significantly affected soybean yields. The only treatment response to tillage for soybeans occurred from the DMI deep plow (48 inch) treatments (DM1 and DM2).

3. Post-tillage penetrometer data indicate that amelioration effects of tillage remain at least four years after initial application of tillage treatments. These deep tilled soils may be subject to recompaction and management plans must include compaction avoidance techniques.

4. Depth of tillage needed to achieve productivity comparable to target yield levels will be affected by initial levels of soil compaction. In this four year study, treatment blocks that were highly compacted (high soil strength) did not achieve the productivity levels of treatment blocks with low initial soil strength levels. Four year mean corn yields and two year mean soybean yields of the shallow (9 inch, 14 inch) and intermediate (32 inch) tillage treatment blocks were poor on soils with high initial strength soils. The DMI deep plows (DM1, DM2) produced corn yields comparable to the undisturbed Cisne soil in three out of four years and equal to the adjusted target yield in all four years of this study.

Figure 5. 1988-89 mean water extraction Jun-Aug vs. mean corn yield.

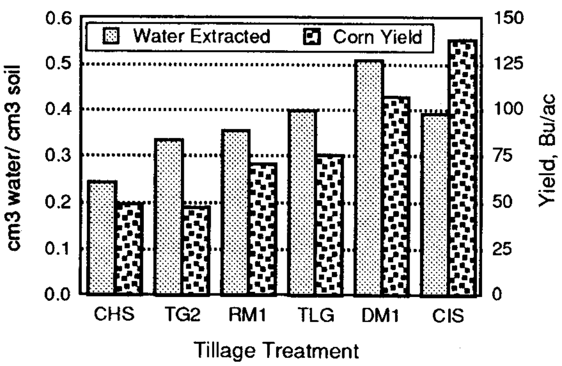


Table 12. 1988-89 Burning Star #2 net water extraction June to August.

TRT	1	2	Depth, ft 3	4	5
			cm³ water/cm³ soil		
			1988		
CHS[1/]	0.071 b	0.066 b	0.050 c	0.030 c	0.003 c
TG2	0.063 b	0.097 ab	0.098 ab	0.086 ab	0.068 a
RM1	0.085 ab	0.107 ab	0.062 bc	0.052 bc	0.037 abc
TLG	0.105 a	0.103 ab	0.088 abc	0.079 ab	0.046 ab
DM1	0.110 a	0.119 a	0.127 a	0.102 a	0.003 c
CIS	0.080 ab	0.135 a	0.097 ab	0.023 c	0.011 bc
LSD(0.05)	0.031	0.046	0.040	0.044	0.016
			1989		
CHS	0.135 b	0.077 b	0.042 c	0.011 cd	0.002 b
TG2	0.131 b	0.078 b	0.037 c	0.002 d	0.008 ab
RM1	0.168 a	0.106 ab	0.059 c	0.021 cd	0.010 ab
TLG	0.155 ab	0.114 ab	0.075 c	0.022 cd	0.009 ab
DM1	0.161 ab	0.138 a	0.126 b	0.076 ab	0.022 a
DM2	0.154 ab	0.150 a	0.180 a	0.104 a	0.009 ab
CIS	0.098 c	0.134 a	0.147 ab	0.048 bc	0.009 ab
LSD(0.05)	0.031	0.046	0.040	0.044	0.016

[1/] Values followed by the same letter within an element and depth are not significantly different at the 0.05 level.

ACKNOWLEDGEMENTS

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Physical Properties of Deep Tilled Surface Mined Soils

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Abstract. Reclamation of surfaced-mined soils for improved crop productivity necessitates amelioration of compacted soil layers to achieve adequate crop rooting. The objective of this study was to measure the residual effects of several deep tillage methods on soil physical and hydraulic properties. Two pedons each of an unmined soil and a mined soil with three tillage methods applied in September 1987 including a standard agricultural chisel plow (30 cm depth),a Kaelble Gmeinder TLG-12 (80 cm depth), and a DM1 ripper (125 cm depth) were examined. The DM1 tilled plots had greater corn or soybean yields than the TLG-12 or chisel plow but did not achieve the yields in an unmined Cisne soil. The physical properties that best distinguished the DM1 treatment were soil strength and to some degree the saturated hydraulic conductivity. Low tension porosity and soil bulk density were less successful in identifying effective treatments that lead to improved grain yields.

INTRODUCTION

Surface mined agricultural land is typically reclaimed by separating topsoil prior to mining, then replacing it after mixed subsoil and overburden materials. The guiding principle of reclamation is that the surface soil has the greatest impact on future agricultural productivity due to its pre-mining enrichment of nutrients and organic matter (Huntington, et al, 1980). Productive soils offer a large rooting zone below the Ap horizon that supplies growing crops with water during the period of greatest evapotranspirational demand. Thus the physical properties on soil material below the replaced topsoil may impact crop productivity on reclaimed soils. Soil structure developed in native unmined soils may offer important avenues for root proliferation and infiltrating water. During mining, the spoil materials may be mechanically dispersed during the removal, storage, and replacement operations (Meyer, 1983; Van Es et al., 1988). Additional trafficking by reclamation equipment may yield compaction and bulk densities above native soils; conditions that may lead to an inferior rooting medium. Compaction of surface mined sites results in high densities well in excess of natural soils (Hooks and Jansen, 1986).

In agricultural soils compacted by heavy farm machinery, freeze-thaw cycles may not provide complete amelioration of dense soil layers (Lowery and Schuler, 1991; Voorhees et al., 1986). Freezing-thawing and wetting-drying have the most effect on surface soil properties because it is there that the greatest environmental extremes occur. Surface mined sites have the unique problem of applied loads occurring as soil is replaced following mining resulting in compaction deep in the final soil profile. These dense soil layers are below the greatest influence of the freeze-thaw cycles.

A potential solution to reduced rooting volume is to apply deep tillage following replacement of all soil layers. Tillage operations that produce a continuous fractured pattern may provide adequate root penetration by annual row crops like corn and soybean. Deep tillage that extends 70 cm or more into the soil profile require enormous machinery power and are not economically feasible to repeat on an annual basis. Recompaction of deep tilled soils is a concern. It has been demonstrated on sandy soils to occur within one year (Busscher, et al., 1986) perhaps due to particle reorientation following wetting and drying (Vepraskas, 1984). The objective of this study was to measure the residual effects of several deep tillage methods on soil physical and hydraulic properties.

MATERIALS AND METHODS

This experiment is located at the Consolidation Coal Company Burning Star #2 mine near Pinckneyville, Illinois. The mine soil at this site was constructed in 1983 using a scraper-haul system to replace 100 cm of rooting media followed by 20 cm of topsoil.

Agronomic practices used during the duration of the study are described in detail in Dunker et al.(1992).

A randomized complete block experimental design providing for six replications of seven treatments was prepared for the site. Two of the six replications were selected for data collection in this study. The two pedons each of the three tillage methods applied on the mine soil in September 1987 and an undisturbed Cisne were evaluated:

Control A nearby tract of Cisne silt loam (fine, montmorillonitic, mesic Mollic Albaqualf) is used as an unmined comparison. The Cisne soil is similar to the pre-mine soils from which the research plots were constructed. Management factors for the mined and unmined soils are the same and similar to practices followed by a typical farming operation in the area.

CHS Standard agricultural chisel plow with an effective depth of 23-30 cm. This treatment is considered the tillage control treatment.

TLG Kaelble Gmeinder TLG-12. The TLG uses a cut-lift operation to shatter the soil to a depth of about 80 cm. A wide, moving foot attached to each of the three shanks cuts and lifts soil as the machine moves forward.

DM1 DMI Deep Ripper (prototype). This machine is a two-lift, solid shank ripper. Two chisel shanks are used to fracture the soil to a 45 cm depth ahead of the main shank. The main shank is parabolic and has a winged point 75 cm wide with an 18 cm lift. The point of the main shank is designed to run 125 cm deep. The machine incorporates a hydraulic trip/reset mechanism to prevent breakage. Under favorable moisture/tilth conditions the floor of the tilled zone shears nearly horizontally, yielding a minimum tilled depth of 120 cm. Moisture content at that depth was a bit high at the time of treatment, and a pronounced ridge of unloosened material was left between shank passes.

The DM1 Deep Ripper treatment was disced prior to tillage to reduce plugging of trash. The TLG was equipped with coulters to eliminate this problem. Immediately after tillage, each plot was leveled with a disc. Tillage treatments were applied to plot areas only once. Each year all the plots are chisel plowed as part of normal fall tillage.

A deep-profile penetrometer (Hooks and Jansen, 1986) was used to measure soil strength after tillage and

Table 1. Tillage equipment description.

Treatment	Power Unit	Horsepower	Tillage Width	Depth of Tillage
			----- cm -----	
DM1	Caterpillar D8LA	440	122	122
TLG	John Deere 850 B	180	230	80
CHS	Ford 6600	85	183	23-30

during crop growing season. Because soil water content has a strong influence on soil strength, in-season measurements were expressed as a fraction of the untilled check. Correcting for concurrent soil strength in the untilled check normalizes the data and allows comparison across years.

Corn (*Zea mays L.*) and soybean [*Glycine max.* (L) Merr] crops rotate each year within the experimental design. A minimum tillage management system was used to minimize traffic and recompaction on the plots. Grain yield samples for corn were harvested after black-layer formation indicated physiological maturity and soybean were harvested when all pods were brown. Grain yield estimates were based on the amount of shelled grain after adjusting for variation in moisture content of grain to 15.5 % for corn and 12.5 % for soybean.

In July 1991, pits were excavated with a backhoe to a depth of 150 cm. Within each 15 cm segment three Uhland cores were inserted laterally into the a cleaned pit-face to obtained an undisturbed soil sample. Hydraulic conductivity was determined in the laboratory using a constant-head method (Klute and Dirksen, 1986). Soil cores were then slowly water saturated, placed in a pressure outflow system (Klute, 1986) and desorbed through a decreasing series of soil water potentials. The cores were equilibrated at 24 h at each pressure step. Bulk density of the cores was determined by oven drying (Blake and Hartge, 1986).

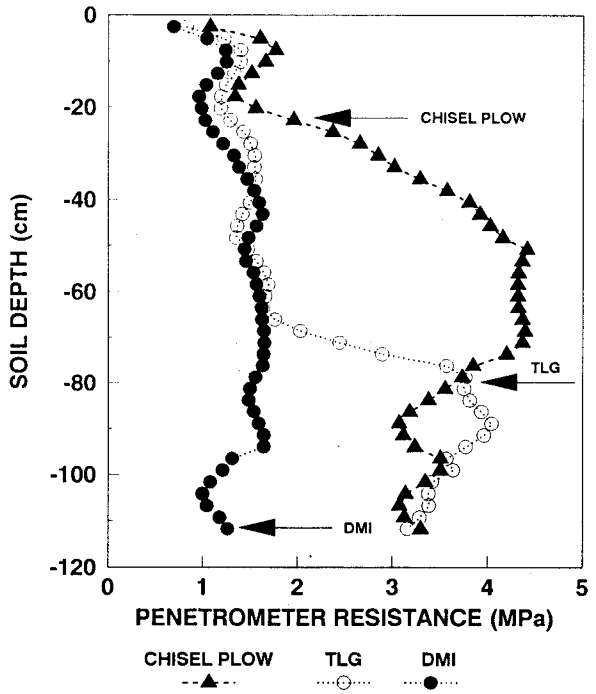
RESULTS AND DISCUSSION

Effects of deep tillage on soil strength

Soil strength measurements using the deep-profile penetrometer were taken prior to planting in 1988, 1989, and 1991 to evaluate tillage effects. Initial soil strength profiles taken approximately 8 months after application of the tillage treatments show close agreement of soil strength reduction and tillage depth (Fig. 1).

Soil strength measurements taken in four depth segments over the four year period following tillage show some reconsolidation or densification (Fig. 2). Data are expressed as a ratio of treatment soil strength:untilled (chisel) mine soil strength. Absolute soil strengths are less meaningful for across year comparisons because soil water content varied between measurement dates. Previous research (Taylor and Gardner, 1963, Thompson, et al., 1987) has suggested that penetrometer resistance, not bulk density, may be a better predictor of root system performance. During the reclamation process, large blocks of naturally compacted soil remain undisturbed when replaced. High traffic reclamation systems will cause additional com-

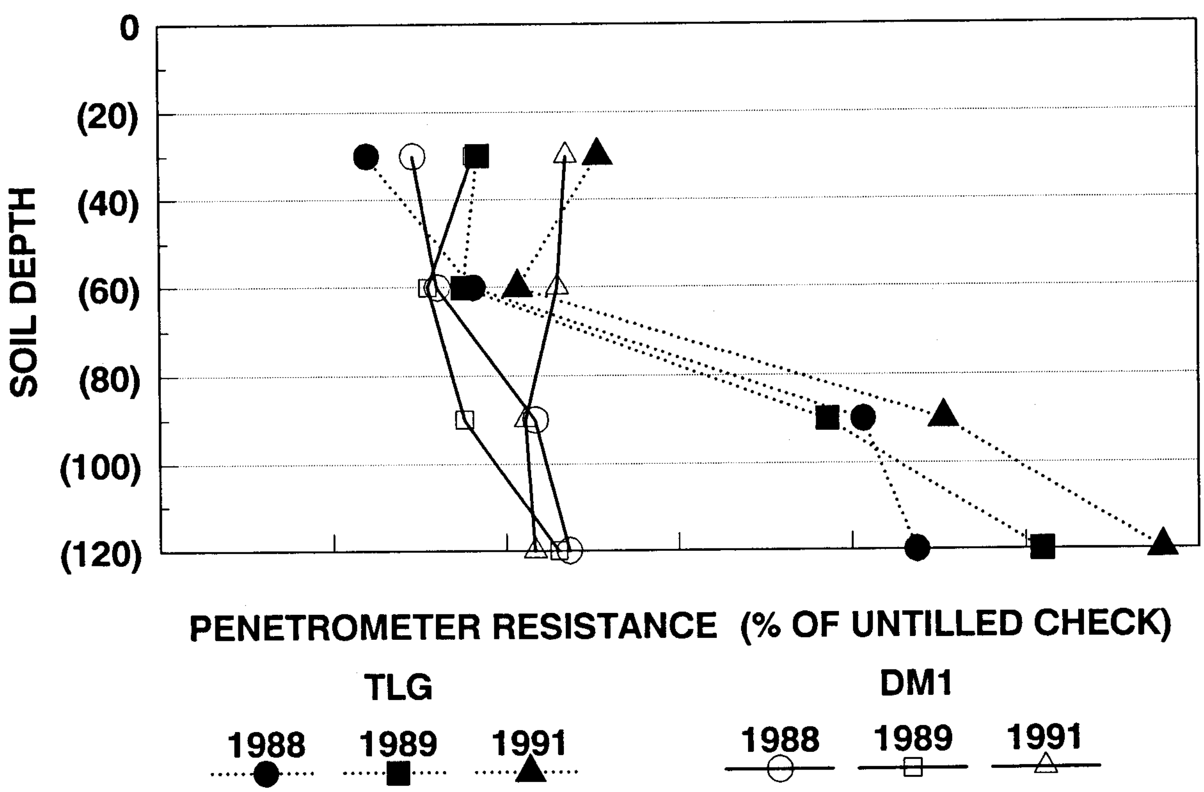
Figure 1. Penetrometer resistance profiles taken eight months (May 1988) after tillage application. Arrows indicate estimated depth of tillage.



paction effects on these soil materials, resulting in a high strength, low porosity soil. Shearing action from deep tillage will create large void spaces within these compacted blocks. Bulk density, which gives a good estimate of porosity within a measured soil unit may tend to underestimate the effects of large voids. Data from this study generally supports this concept, as variation in yields among treatments appear to be more closely associated with differences in observed soil strength levels than with differences in observed bulk densities. The DM1 treatment continues to remain at 0.5 or 50% of the untilled soil strength through most of the soil profile. Soil horizons down to 80 cm in the DM1 treatment appear to exhibit somewhat more soil strength with each passing year. The TLG treatment also appears to be gaining strength down to 80 cm below which point there is no apparent difference over time.

Soil bulk density was not as sensitive as the penetrometer to tillage method. Four years after tillage the DM1 showed slightly less bulk density than the TLG or chisel treatment at depths below 50 cm (Fig 3.). All treatments exhibited bulk densities greater than the control plot in undisturbed Cisne silt loam. This probably is attributed to the method of sampling that is biased towards the more coherent portions of the soil pedons. The penetrometer, in contrast is not a biased

Figure 2. Penetrometer resistance for the DMI and TLG treatments for three years after tillage application. Data are expressed as a fraction of soil strength measured in mined untilled soil.



sampling technique because it includes the entire soil volume.

Saturated hydraulic conductivity values for the TLG and DM1 treatments still reflect the influence of tillage disruption at significant depths (Fig. 4). The DM1 treatment has higher saturated hydraulic conductivity than the unmined comparison soil at the 70-100 cm depth. Porosity values derived from the 0-440 cm tension range of the soil water characteristics show little difference between treatments (Fig. 5). This lack of difference contrasted with the differences in hydraulic conductivity suggest that the distribution of pore sizes is different between treatments. Large conducting pores that allow for greater saturated water flow probably still exist in the deep tilled DM1 plots. The sharp slope in the first 100 cm of tension at the 60-75 cm depth of the DM1 suggests that a rapid dewatering of macropores occurs under low tensions, thereby exhibiting a higher saturated hydraulic conductivity (Fig. 6).

Grain yields over the four year period following deep tillage were highest on the DM1 plots (Table 2). The TLG treatment increased corn yield in only one year out of four and never equalled the unmined soil. However, only in 1991, under an overall reduced yield environment, did the DM1 match the corn yield of the unmined Cisne silt loam.

Figure 3. Bulk density profiles of chisel plow, TLG, and DMI tilled mine soils compared with an unmined Cisne silt loam (control) taken four years after tillage application.

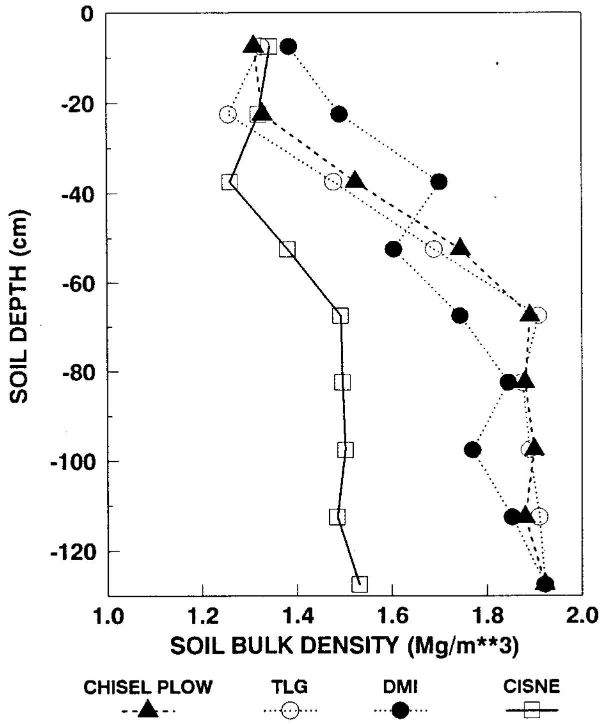


Figure 4. Saturated hydraulic conductivity profiles for chisel plow, TLG, and DM1 soils compared with an unmined Cisne silt loam (control) taken four years after tillage application.

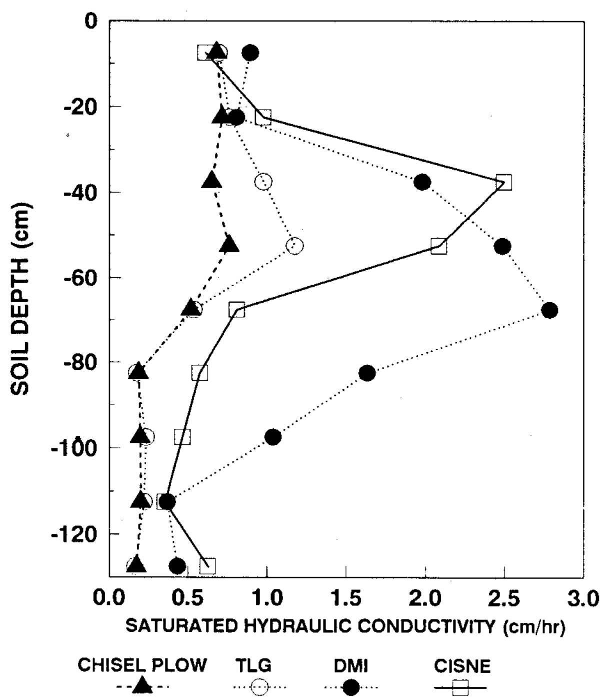


Figure 5. Porosity profiles (0-440 cm tension) for chisel plow, TLG, and DM1 soils compared with an unmined Cisne silt loam (control) taken four years after tillage application.

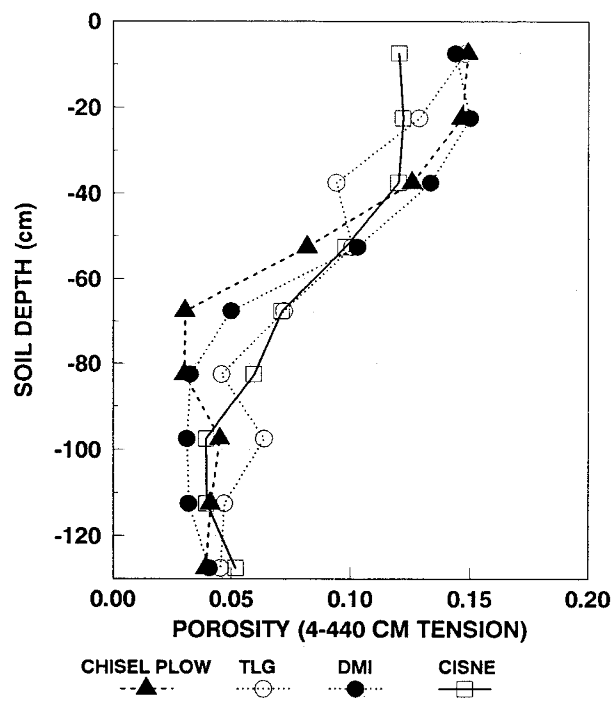


Figure 6. Soil water characteristics for 5 soil depths in chisel plow, TLG, and DM1 treated soils taken four years after tillage application.

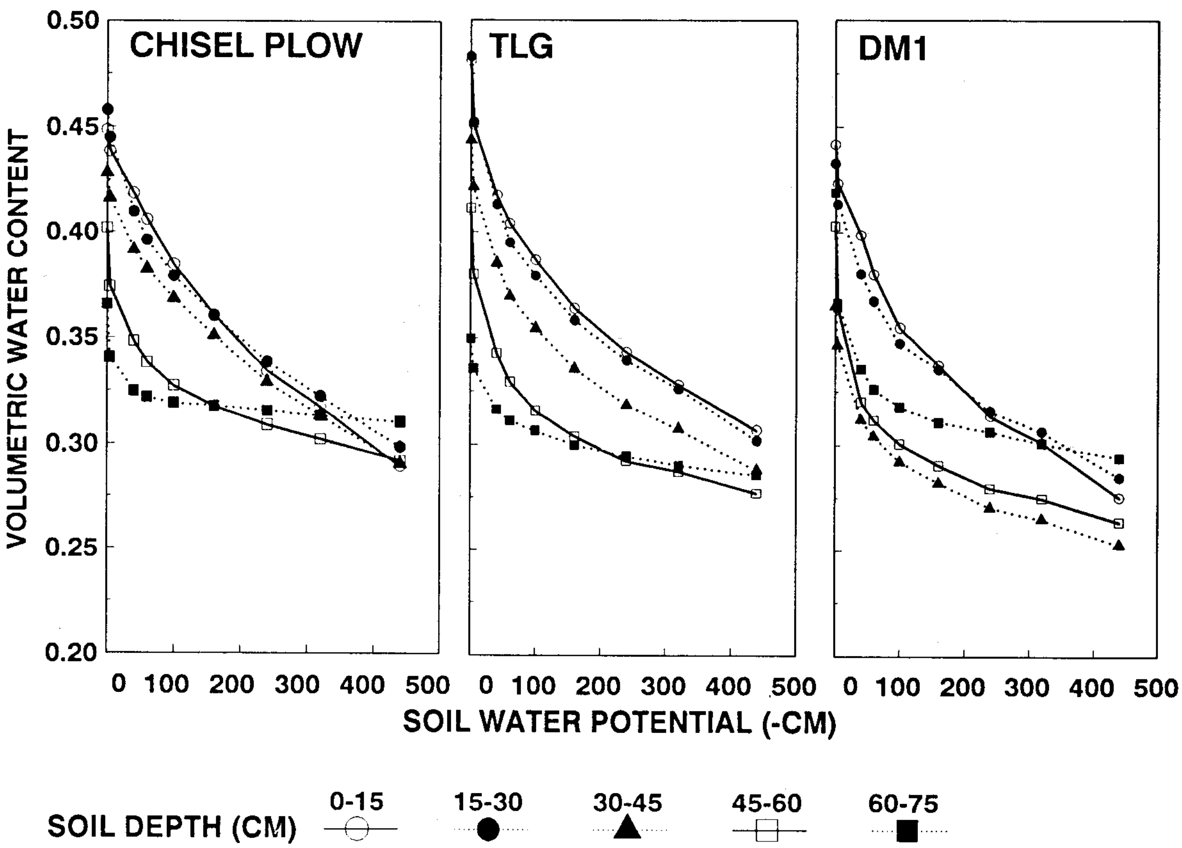


Table 2. Tillage effects on corn and soybean grain yields for 1988-1991 in harvest area adjacent to soil property study.

Treatment	1988	1989	1990	1991	Mean
	Grain Yield (bu ac^{-1})				
			Corn		
CHS[1/]	25.8 d[2/]	63.3 c	21.9 c	7.2 b	35.6 d
TLG	58.4 c	73.1 c	26.1 c	16.0 b	93.3 b
DM1	91.9 b	125.1 b	75.4 b	61.8 a	58.9 c
Cisne	135.7 a	141.6 a	130.3 a	68.3 a	118.5 a
			Soybean		
CHS	13.1 b	8.7 b	*[3/]	*	
TLG	12.9 b	10.0 b	*	*	
DM1	21.7 a	17.3 a	*	*	
Cisne	18.7 a	23.7 a			

[1/] Tillage treatments: CHS, conventional chisel plow, 8" tillage depth; TLG, Kaeble-Gmeinder TLG ripper, 32" depth; DM1, DMI deep plow 48" depth; Cisne, unmined Cisne soil (control).

[2/] Values followed by the same letter within a year are not significantly different at the 0.05 level.

[3/] No sample

Grain yields for this study were measured on the west side of the Burning Star site where pre-tillage evaluations with a cone penetrometer showed greater soil strength than the east side of the mine (Dunker, et al., 1992). The greater compaction was attributed to trafficking during reclamation. Corn and soybean grain yields on the west side of the mine have been significantly lower than the east side since reclamation suggesting that initial level of compaction may determine the depth of tillage needed to achieve productivity.

The physical properties that best distinguished the DM1 treatment were soil strength and to some degree the saturated hydraulic conductivity. Low tension porosity and soil bulk density were less successful in identifying effective treatments that lead to improved grain yields.

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Computer Tracking of Revegetation Operations using RODA

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Abstract. Revegetation bond release is based on an area achieving target yield levels for certain crops during the responsibility period. Record keeping of farming operations on hundreds of AMAX farm fields covering thousands of acres became a monumental task both for the field and office personnel. Revegetation Operations Data Analysis (RODA) is a database management system which is designed to track revegetation operations and reclamation progress on farm fields.

Each farm field has a clock which defines the time since topsoil replacement and initial seeding. The clock may be restarted if an operation is done to the field which is defined by the regulatory authority as augmentation. For example, Illinois Department of Mines and Minerals(IDMM) considers a major replanting of trees on a forest area where the initial planting failed to be augmentation. The clock for the responsibility period is restarted.

Once the background data (location, size, initial seeding, etc.) for a farm field has been entered into RODA, field activities are input as they are performed. RODA keeps track of the progress toward achieving the successful yields on the combination of required crops for bond release. Executive reports summarize the status of all farm fields within a permit.

The second objective of RODA is to monitor revegetation costs. Labor, equipment, and materials costs are input for jobs performed and RODA can provide a detailed costing both by the area and by the individual job. RODA costing data is used in evaluating revegetation options and in preparing budgets.

DESCRIPTION

The database management system for RODA is structured around two objects: codes and fields. Every activity, material, and crop dealt with by RODA has a unique code. An entire module of RODA is dedicated to the maintenance of the master codes.

The other primary object in RODA is a farm field. Planting, tilling, harvesting, and yield compliance are all done on a field basis. Nearly all of the data files in RODA are referenced to farm fields at a mine location.

An overview of the information flow for RODA is summarized in Figure 1. Ayrshire Land Company (ALC) field personnel at the AMAX coal mines enter the codes and field locations where work has been completed. Labor and equipment are recorded on Table 1, materials applied on Table 2, and harvest yield data on Table 3.

The tables are sent to ALC office at Sullivan, Indiana for data entry into RODA. In addition, costs for labor, materials, equipment, and vendor services are entered into RODA at Sullivan based on invoices paid.

Permit and bond tracking information is entered at the AMAX Coal Company (ACC) office in Evansville. Farm field maps are updated as new areas are reclaimed. Target yields are entered for each permit.

RODA operates on an IBM VM/CMS mainframe computer located in Indianapolis. The database management system is Adabas and the program is written in Natural. Reports listed on Figure 1 can be accessed at individual mine locations, ALC office in Sullivan, or the ACC office in Evansville.

RODA STRUCTURE

RODA is organized into four modules or groups of functions. They are:

- Revegetation Operations Tracking and Costing
- Permits, Fields, and Bond Release Tracking
- Master Code Information
- Miscellaneous Items

These modules are selected from RODA's main menu. Options available in each module will be discussed in more detail.

Revegetation Operations Tracking and Costing

This module tracks the field activities performed on each area and what each costs. Field personnel record work done on three data input tables:

1. Equipment and labor field log of work performed
2. Materials applied log
3. Harvest yield data log

Figure 1. RODA information flow chart.

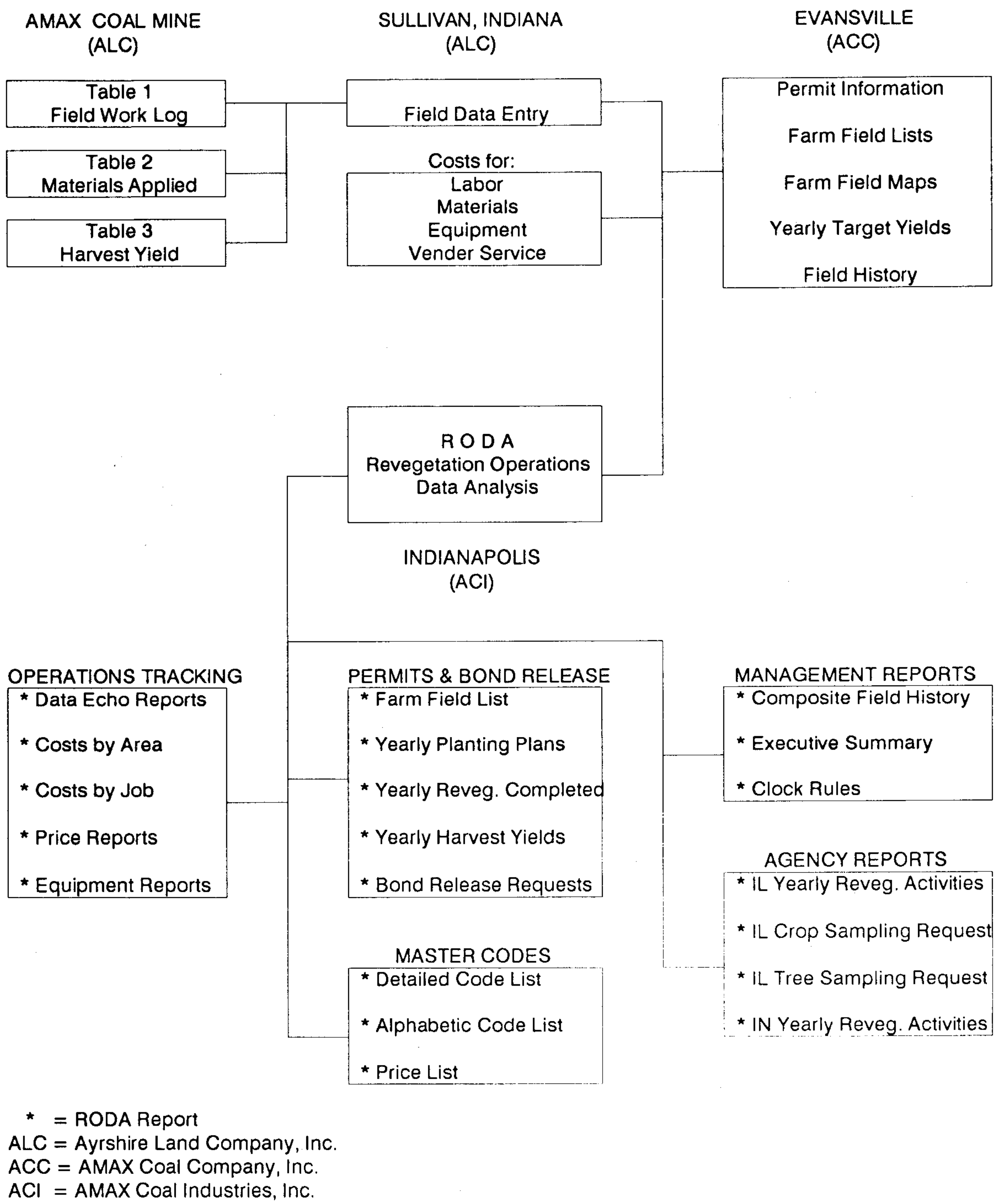

Table 1 is kept in the tractor or power unit. The operator records the identification number for the implement being used on each area as the work is being performed. This field log identifies labor and equipment being utilized on each area. Work performed by vendors can also be recorded in Table 1.

Table 2 on materials applied is normally completed by the revegetation manager for a mine location. Material codes and rates are itemized by farm field or miscellaneous area.

Table 3 on harvest yield is also filled out by the manager based on yield records.

Ayrshire Land Company office personnel located in Sullivan, Indiana, input data for the remaining functions in revegetation operations:

Table 1. Equipment & labor field log of work performed.

POWER UNIT

NAME ____________________

ASSET ID NO. ____________

MINE ____________________

WEEK ENDING ____________ (mm/dd/yy)

TABLE 1 Page ___ of ___

DATE	AREA	COVERAGE		PRIME	TOTAL HOURS	EQUIPMENT HOURS OR MILES			IMPLEMENT		POWER UNIT		
mm/dd	ID	acres	trip x	JOB DONE	INCLUD. REPAIRS	START	FINISH	TOTAL	ID NO.	REPAIR HOURS	FLUID TYPE	QUAN.	REPAIR HOURS

Table 2. Materials applied log.

MINE ____________________

WEEK ENDING ____________ (mm/dd/yy)

TABLE 2 Page ___ of ___

DATE	AREA	TOTAL	M OR	VENDOR APPL.		WORK DONE		MATERIALS APPLIED					
mm/dd	ID	ACRES	V	CODE	TOTAL COST	JOB	METHOD	CODE	RATE/ ACRE	CODE	RATE/ ACRE	CODE	RATE/ ACRE

Table 3. Harvest yield data log.

MINE ____________________

WEEK ENDING ____________ (mm/dd/yy)

TABLE 3 Page ___ of ___

DATE	AREA	TOTAL	M OR	WORK DONE		CROP	YIELD		TOTAL	VENDOR HARVEST EXPENSES			
mm/dd	ID	ACRES	V	JOB	METHOD	CODE	No. BALES	TOTAL HARVEST	INCOME	CODE	TOTAL COST	CODE	TOTAL COST

Labor prices
Master code prices - materials
Equipment list
Equipment repair invoices
Equipment depreciation
Vendor list
Master code prices for vendor costs

Labor, material and equipment prices have an effective date when entered. RODA can cost work functions using the prices in effect at the time the work is performed. Prices may be updated as often as desired. The reports in the Revegetation Operations Cost Tracking module include:

- Echo reports
  - Equipment and labor field log
  - Materials applied log
  - Harvest yield log
- Costing reports
  - Activity costs by area
  - Activity costs by job
- Price reports
  - Labor prices
  - Master code prices
- Other reports
  - Vendor list
  - Equipment list
  - Equipment depreciation
  - Equipment cost & usage
  - Month closing status

PERMITS, FIELDS, AND BOND RELEASE

This module contains all functions needed to track the bond release status of any farm field. Included are maintenance and field information, field summary information, pre-RODA field history, and reclamation rules. The data maintenance functions include:

Farm field list
Yearly plans
Yearly planting summary
Yearly yields/standards checks
Yearly bond release requests/approvals
Pre-RODA reclamation history
Pre-RODA field numbers
RODA reclamation clock rules
Permit list
Yearly target yields

Since tracking bond release on individual farm fields is the primary objective of RODA, further detail is provided for each of the tracking and costing function in this module.

Farm Field List

This function maintains information about each farm field tracked by RODA. This base level information identifies the background needed by RODA to apply reclamation clock rules in order to determine revegetation success. Included in the field's information are field number, mine number, post-mining land use, land capability, regulatory program, date topsoil replaced, soil thickness, and ownership. Each operation has a farm field map showing the location of individual fields. The map is updated as topsoil is replaced and new fields are entered into RODA.

Yearly Plans

This function maintains the yearly planting plans for each field. Information recorded can include crops to be planted, acres to be held in conservation practice, and whether yields are to be checked by the Regulatory Authority. For example, Illinois Department of Agriculture requires operators to report by February 15 each year on specific fields which will need to be sampled for yield. RODA can generate this agency report using the yearly plans data input.

Yearly Planting Summary

This function maintains the yearly summaries of planting and fertilizing activities completed for each farm field. In contrast to the yearly plan, the planting summary records what crops or trees were actually planted, as well as augmentation activities. This file is the primary source of information for the annual revegetation activities report sent to the regulatory authority.

Yearly Yields/Standards Checks

This function summarizes the harvest information for each year. Yield levels are compared against the required target yield to determine compliance.
Yearly bond release requests/approvals

This function is primarily a record-keeping tool for recording dates that requests were made for revegetation bond release and when approval is received for an area.

Pre-RODA Reclamation History

RODA has tracked revegetation activities at AMAX since 1988. Farm fields topsoiled prior to 1988 can be summarized in RODA using the history function so that the clock status can be defined. Crops planted and yield success status are the key elements entered in the reclamation history.

Pre-RODA Field Numbers

This allows entry of field numbers used for specific years prior to implementation of RODA records.

RODA Reclamation Clock Rules

The rules by which states determine that a field meets revegetation requirements are recorded in this module. The RODA coordinator can identify the rules which start or restart the clock, and the combination of crop successes needed for bond release. Specific rules are defined within RODA for each state. The rules are used by RODA to determine bond eligibility success for individual fields.

Permit List

This function records and modifies information about the permits involved in RODA.

Yearly Target Yields

This function records target yield information used in determining whether a field has met standard for a year. Yields for each crop and land capability can be entered.

RODA REPORTS ON PERMITS, FIELDS, AND BOND RELEASE

When the data maintenance function has been updated for a permit, the following reports may be generated by RODA:

Field/permit reports
- Farm field list
- Yearly plans
- Yearly planting summary
- Yearly harvest yields and standards checks
- Yearly bond release requests and approvals
- Permit list
- Yearly target yields

Management reports
- Composite history of farm fields
- Executive summary of bond release status
- Bond release clock rules for RODA

Agency reports
- IL yearly revegetation activities report
- IL yearly request for crop sampling
- IL yearly request for tree sampling
- IN yearly revegetation activities report

MASTER CODE INFORMATION

This module maintains all coded items, from crops to job activities. RODA codes are composed of from 1 to 6 letters and/or numbers. Examples of codes used are presented in Table 4. The primary data maintenance functions under Master Codes include:

- Master code list
- Master code prices - materials
- Master code prices - vendor charges

New codes may be added to RODA as needed. The codes are grouped as follows:

- Field work codes
  - Areas
  - Jobs
  - Methods

- Other Codes
  - Vendor application charges
  - Vendor harvest charges
  - Nutrients

- Species codes
  - Row crops
  - Legumes
  - Grasses
  - Seed blends
  - Trees and shrubs

- Species variety codes
  - Row crops
  - Legumes
  - Grasses
  - Seed blends

- Material Codes
  - Fertilizers and lime
  - Mulches
  - Tackings
  - Pesticides

Table 4. Example of RODA codes used for field data entry

AREA ID

#	Field Number
AA	Ancillary Area
BA	Basin
HR	Haul Road
MA	Miscl. Area

JOB DONE TO EQUIP

PM	Preven. Maint.
R	Repairs

JOB DONE TO AN AREA

AF	Apply Fertilizer
AFC	Apply Fert-Corn
ALIM	Apply Lime
AP	Apply Pesticides
APC	Apply Pest-Corn
CM	Crimp Mulch
DR	Debris Removal
EC	Erosion Control
ECBB	EC-Bale Buster
ECFM	EC-Finn Type
H	Harvest
HCO	Harvest-Corn
LL	Land Level
LT	Load/Transport
LTCO	LT Corn
MJ	Miscellaneous Job
MOW	Mow
PLT	Plant
PLTC	Plant-Corn
RA	Raking
T	Tillage
TCUL	T Cultimulcher
TD	T Deeper than 24"
TDSK	T Disk
VT	Vendor tillage
VTD	VT Deeper than 24"

FLUID TYPE & UNITS

ANFZ	Antifreeze (qts)
D	Diesel (gal)
G	Gasoline (gal)
HY	Hydraulic Fluid (qts)
OIL	Oil (qts)
TR	Trans. Fluid (qts)

FIELD WORK: METHODS

AB	Aerial broadcast
BR	Baling round
DP	Drill or planter
GB	Ground broadcast
HP	Hand plant
MP	Machine plant

MATERIALS: MULCHES

HMUL	Hydromulch fiber
HRBN	Hay, round bale, No.
SSBT	Straw, sq. bale, ton
WC	Wood chips

MATERIALS: TACKINGS

CHV	Curlex-high velocity
ENET	Erosion netting
ENKA	Enkamat 7010
NAPM	N.A. P300 polymat

MATERIALS: PESTICIDES

ATZ	Atrazine
BRON	Bronco
FUR	Furdan
KER	Kerb
LASO	Lasso
LORS	Lorsban
RUP	Roundup

FERTILIZER/LIME

F0060	Muriate of potash
F0440	Tri. super phosphate
F1846	Ammonium phosphate
FB1	Fertilizer-borate 40
FZN1	Fertilizer-zinc sulfate
F1212	Fert. blend 12-12-12
L1	Lime-calcite

VENDOR APPLICATION CHARGES

VA1	Ground broadcast
VA8	Machine plant trees
VA13	Vendor tillage
VA19	Vendor cultimulcher
VA20	Replant trees by hand
VA22	Ground spray

VENDOR HARVEST CHARGES

VH1	Combine wheat
VH2	Combine corn
VH5	Baling, square
VH8	Transport bales, round
VH9	Transport grain

TREES/SHRUBS

APL	American plum
BC	Black cherry
CHO	Chestnut oak
GRA	Green ash
HAW	Hawthorn
HZNT	Hazlenut
MUL	Mulberry
REO	Red oak
RIB	River birch
SUST	Sumac, staghorn
WHO	White oak

GRASSES

OG1	Orchardgrass
RG1	Annual ryegrass
RT1	Red Top - common
SB2	Smooth brome-Beacon
TF2	Tall fescue-Fawn

LEGUMES

AC1	Alsike-common
AL1	Alfalfa-Vernal
AL15	Alfalfa-Cargill Crown
BT1	Birdsfoot trefoil
LC1	Ladino-common
RC1	Red clover-common

ROW CROPS

CO1	Corn-Pioneer 3377
CO17	Corn-GH 2572
MI1	Millet-Pearl
MI3	Millet-German
SO1	Soybeans-Williams
WH3	Wheat-Pioneer 2555
WH8	Wheat-Dynasty

Equipment fluids

Material variety codes
Fertilizers and lime

All of the codes are stored in the RODA-CODES file. When a new code is added, the purchase rate unit and application rate unit must be provided so that RODA will be able to determine total costs for the materials applied.

MISCELLANEOUS ITEMS

This module is a catch-all for RODA maintenance functions. It contains the mine list, user list, and user messages.

COMPUTATIONAL PROCEDURES

Revegetation costs for a field is made up of 4 components:

Labor cost
Materials cost
Equipment cost
Vendor charges

Labor cost is the product of the man-hours recorded on the field log for an activity times the average labor unit price for a mine location.

Materials cost is calculated knowing the rate applied to an area (Table 2) and the unit price.

Equipment cost is recorded for the field in units of equipment usage (miles or hours). The equipment cost rate is made up of 4 components:

material cost: used to run and repair the unit
repair labor cost: ALC repair cost
vendor repair cost: charges made by vendors
depreciation cost: monthly decrease in value

The four costs are totaled for the equipment's life-to-date, then divided by the equipment's usage(hours or miles). This cost per usage unit is then used to determine the equipment cost for an activity on a farm field.

RODA activity costs are approximate since the system is not designed to be a rigorous accounting program. It allows the revegetation manager to identify costs for individual farm fields or jobs so that cropping options can be evaluated when preparing yearly plans and reclamation audits.

BOND TRACKING REPORTS

Examples of the three most helpful RODA reports for tracking revegetation bonds will be discussed in further detail. Table 5 is an example of the yearly revegetation activities report (SCML 4 report to IDMM). This report identifies when a field was initially planted with crops or trees, and when augmentation has been done to the field which starts or restarts the clock. Field R305 is high capability cropland which was initially seeded in 1988. Since deep tillage is needed in this permit on all high capability areas, the clock starts in

Table 5. Example of RODA agency report.

SCML–4 Report to: Illinois Department of Mines and Minerals
YEARLY REVEGETATION ACTIVITIES REPORT

Calendar Year: 1990

Company: AMAX Coal Company   Mine: Delta   Pit Name: C&H East

Permit No.	Field No.	OSM Program	Land Use Capab.	Total Acres	Year of Topsoil Approval	Planting Activities: Type Veg.	Amendments Code	Amendments Rate	Species/Variety Code	Species/Variety Rate	Augmentation 1990: yes/no Comment Latest Year
82	R305	PP	CL HC	32.5	1988	CR	F1846 F0060 L1	300 300 5	WH3	120	1990: yes DMI Sup'r Tiger
82	W403	PP	WL NCC	45.2	1987	PV	F4600 F1846 F0060	100 100 100	WHO REO RIB MUL HZNT HAW	125 125 85 40 40 40	1990: no

1990 when the field is deep ripped using the DMI Sup'r-Tiger. Likewise, the clock on W403 wildlife area begins when the area is planted to trees and shrubs in 1990.

An example of the composite history of farm fields to determine eligibility for bond release is presented in Table 6. The table summarizes the background information on the farm field; what crops have been planted and whether target yield was achieved; when augmentation or a major replant of trees occurred; and the clock status. Field R411 was deep tilled in 1987 to start the clock. The target yields for wheat, hay, and corn were achieved in the following three years so it qualifies for bond release.

For the wildlife field W401, the initial tree planting in 1986 failed and a major replant was made in 1988. The clock was restarted and the trees met the standard when checked in 1991. Deep tillage is not needed on this field since the capability is non-crop.

The composite history is the most important report in RODA since it summarizes relevant information and reaches the bottom line conclusion on when a field qualifies for bond release. Rules used to determine eligibility change when an agency revises the regulations, but RODA can evaluate eligibility on the rules in effect when the field was initially reclaimed.

The third report is the Executive Summary of Bond Release Status (Table 7). For each clock year in both the interim and permanent programs, RODA gives the acres which do and do not meet the standards in a given year (1990). For example, for interim program areas where the clock does not restart, 382.2 acres qualified in 1990, and 509.7 acres remain which do not meet the revegetation standard. A similar breakout by clock year is presented for the permanent program fields. In 1990, 86.0 acres qualified and 1156.8 acres do not qualify for revegetation bond release.

CONCLUSIONS

RODA is a database management system for tracking revegetation activities on reclaimed farm fields. The primary objective is to determine eligibility of the field for revegetation bond release based on applying the rules established by the appropriate regulations. The secondary objective is to monitor costs associated with revegetation activities for use in future planning.

Annual reporting required by the Regulatory Authorities can be done using RODA. Field history can be summarized and the eligibility for bond release determined automatically. Costs can be broken out by area or by job so revegetation managers can determine the most cost effective procedures for each postmining land use.

RODA operates on the AMAX mainframe computer to allow easy access from multiple locations. The program could be adapted to smaller personal computers if a good local area network(LAN) serviced all locations. Currently, AMAX does not plan to convert RODA to personal computers.

As with any large database management system, it took considerable time and effort to input the background information on the hundreds of farm fields being tracked. It also takes consistent effort by the field

Table 6. Example of RODA farm field history report.

COMPOSITE HISTORY OF FARM FIELDS TO DETERMINE ELEGIBILITY FOR BOND RELEASE

Company: AMAX Coal Company Mine: Delta Pit Name: C&H East

Permit No.	Field No.	OSM Program	Land Use Capab.	Total Acres	Year of Topsoil Approval	Year	Type Veg or Crop Harvestd	Made Traget Yld?	Augmen?	Major Replant?	Clock	Qual. for Reveg. Bond Release
81	R411	PP	CL/PF	41.3	1986	1986	MI	no	no		PC0	no
						1987	WH	yes	yes		C1.0	no
						1988	WH	yes	no		C1.1	no
						1989	HA	yes	no		C1.2	no
						1990	CO	yes	no		C1.3	yes
81	W401	PP	WL/NCC	66.5	1985	1985	GV	no	no	no	PC1	no
						1986	GV	no	no	yes	C1.0	no
						1987	TS	no	no	no	C1.1	no
						1988	TS	no	no	yes	C2.0	no
						1989	TS	no	no	no	C2.1	no
						1990	TS	no	no	no	C2.2	no
						1991	TS	yes	no	no	C2.3	yes

personnel to report daily revegetation activities. However, once the information is entered in RODA, detailed reports can easily be generated for tracking bond release status of farm fields and determining detailed costs for revegetation activities.

Table 7. Example of RODA executive summary of bond release status.

EXECUTIVE SUMMARY OF BOND RELEASE STATUS

Year: 1990
Mine: Delta

Clock Year	Acres Meeting Revegetation Standards In: 1990	RODA–Tracked Acres Which Do Not Qualify for Bond Release									Remaining Total Acres
		Prime		High Capability/Crop Capable				Non–Crop Capable			
		CL	P	CL	P	F	WL	P	F	WL	
Interim Program											
IP6	146.2	0.0	0.0	44.1	54.7	0.0	0.0	122.0	0.0	24.2	245.0
IP7	53.4	0.0	0.0	46.4	3.0	0.0	0.0	0.0	27.7	5.8	82.9
IP8	40.4	0.0	0.0	55.0	11.2	0.0	0.0	15.4	0.0	20.4	102.0
IP9	142.2	0.0	0.0	0.0	76.0	0.0	0.0	0.0	3.8	0.0	79.8
Total – IP	382.2	0.0	0.0	145.5	144.9	0.0	0.0	137.4	31.5	50.4	509.7
Permanent Program											
PC0	0.0	91.9	0.0	3.7	39.4	0.0	0.0	0.0	34.1	0.0	169.1
PC1	0.0	10.5	0.0	1.9	5.5	4.5	0.0	0.0	42.0	0.0	64.4
PC2	0.0	0.0	0.0	0.0	0.0	25.4	0.0	0.0	0.0	0.0	25.4
PC3	0.0	0.0	0.0	4.3	59.8	14.6	0.0	0.0	15.9	0.0	94.6
C1.0	0.0	15.8	0.0	0.0	25.3	0.0	0.0	14.7	143.2	0.0	199.0
C1.1	0.0	0.0	0.0	44.5	0.0	17.6	0.0	0.0	0.0	15.9	78.0
C1.2	0.0	65.6	0.0	11.7	163.4	0.0	0.0	0.0	31.2	0.0	271.9
C1.3	41.3	0.0	0.0	0.0	68.3	0.0	25.7	9.0	0.0	0.0	103.0
C1.4	44.7	0.0	0.0	0.0	0.0	0.0	0.0	85.4	0.0	0.0	85.4
C2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.0	66.0
Total – PP	86.0	183.8	0.0	66.1	361.7	62.1	25.7	109.1	266.4	81.9	1156.8

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Air Injection of Organic Material During Deep Tillage to Prevent Soil Recompaction

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Absract. Although deep tillage is recognized as an effective means of reducing compaction in reconstructed soil, the benefits achieved may be lost due to recompaction. A research investigation was initiated to study the possibility of using air to inject organic material into the voids created by the tillage operation. A laboratory model demonstrated, with some success, that the injection of low-density organic material could reduce the amount of recompaction that occurs. This paper addresses the conceptual design of a full-scale tillage device that integrates pneumatic injection of amendments into the deep tillage process. The basic components of the system are discussed and consideration is given to the impact that the subsoiler shape has on the flow path of the injected material. Also, attention is given to the material characteristics that are most appropriate for injection.

INTRODUCTION

Certain events are known to reduce the pore space created by deep tillage operations (Simpson et al., 1991). Kouwenhoven (1986) studied the effects of natural events, such as rain, gravity, and shrinkage, on tilled soils. It was discovered that even without traffic, some of the newly created macropores will collapse. Larney and Fortune (1986) studied the effects of subsequent cultivation on previously tilled soils. This work determined that while massive soils have the greatest need for deep tillage, the additional cultivation passes required for clod breakup can cancel the effects of deep tillage in some cases.

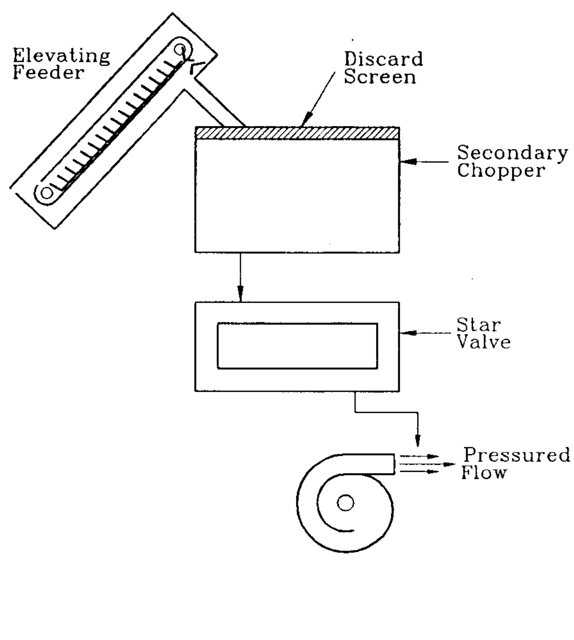
The conventional approach to preventing recompaction involves management practices aimed at minimizing the compactive effort applied to soil that has been deep tilled. Specially designed low ground pressure agricultural equipment has been used for this purpose.

The authors have proposed an alternative approach that is based upon the pneumatic injection of low-density organic material into the voids at the time of deep tillage. It is hypothesized that the injected material will preserve the integrity of the newly created macropores allowing roots to explore and air and water to migrate freely. A model study was conducted to test this hypothesis.

OVERVIEW OF MODEL STUDY

The major components of the model are shown in Figure 1 (Simpson et al., 1991). Belknap soil, prime farmland silt loam subsoil, was used in the study. It was compacted initially in the soil bin in lifts of approximately 6 inches each, using a one square foot metal plate attached to the bottom of a hydraulic cylinder. When the bin was filled to a depth of approximately 36 inches, the soil was ripped with an agricultural subsoiler that had been modified to permit air injection of material at the rear of the ripper foot. Following ripping and material injection, the soil was recompacted in the same manner in which it was compacted initially.

Figure 1. Schematic diagram of air and material injection laboratory model system (Simpson et al., 1991).



Following each stage of the test (i.e., initial compaction, ripping and injection, and recompaction), a battery of soil evaluations were performed. These evaluations included the determination of bulk density using both the gravimetric method and the nuclear method, measurement of mechanical resistance to cone penetration, and a determination of the hydraulic conductivity of the soil.

Due to the limitations of the injection system, only granular materials were used as soil amendments. The materials that were used are slag product (sand), ground walnut shells, and ground pecan shells. These materials were selected only for test purposes due to their variation in density and aerodynamic properties. For actual field applications it is anticipated that typical agricultural by-products such as straw mulch, wood chips, or horse bedding would be used.

Results from the model study gave cause for cautious optimism. While it could be observed visually upon excavation that material had been injected along the crescent failure surfaces caused by ripping, a number of the soil evaluation methods showed no positive residual effect of injection. This can be explained partially by the uncertainty of whether the points sampled actually fell in an area that was affected by the injection process. Gravimetric bulk density, hydraulic conductivity, and penetrometer resistance measurements all suffered from this shortcoming. However, the nuclear bulk density measurements, which measure the average bulk density between two probes, indicated a residual positive effect for some materials.

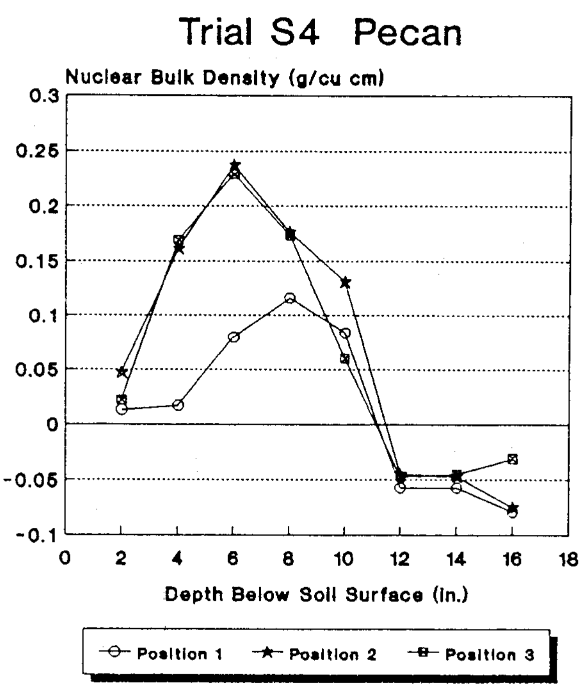
This method used a CPN Model MC-S-24 dual-probe nuclear density guage. The probes are separated by a distance of 12 inches. Measurements were taken within the ripped zone of the model at depth intervals of 2 inches from the surface downward to the maximum depth of penetration, which was approximately 12 inches. The greatest residual effect was observed with the injection of pecan shells. The difference between initial density and recompacted density as a function of depth is shown in Figure 2 for three positions within a bin that used pecan shells as the soil amendment. Positions 1, 2, and 3 represent the locations where nuclear bulk density measurements were taken in the bin. These measurements were made along the centerline of the bin at a spacing of approximately 12 inches. Position 1 was closest to the front of the bin and ripping progressed in the direction from Position 3 to Position 1. The measurement that is reported in Figure 2 is the difference between the initial density, which was measured following compaction but before any ripping or injection was performed, and the final density that was determined following ripping and recompaction. Therefore, a positive number indicates a lower residual density following treatment and recompaction. These tests demonstrated a fairly strong residual effect in the range of 0 to 10 inches. This would seem to indicate that injection of the low-density organic material had prevented significant recompaction in these cases.

PROTOTYPE SOIL INJECTION SYSTEM DESIGN CONSIDERATIONS

The purpose of injection is to place innocuous organic material into the soil during the process of deep tillage for the purpose of preventing recompaction of the soil after tillage. In addition to its role as a soil lightener, as this material decomposes, it is conjectured that it will allow for the passage of air and water to plant roots, which should lead to improved soil structure. Decomposing organic matter may also contribute nutrients to growing plants. It may be noted also that this system could be used to place farm or other benign organic wastes into a soil for the purpose of disposal.

The laboratory experimental system, with its closed and pressurized container, used a non-continuous system of delivery of soil amendment. The objective of this portion of the study is to give initial shape to the plans for a prototype field injection system. It is desired to have a system that is rugged, will deliver most types of organic waste without plugging, and that will have a

Figure 2. Difference between initially compacted and recompacted density as a function of depth for air injection of ground pecan shells (Simpson, 1991).



capacity consistent with field size and loading rates. Some of the ideas that are presented here have been used to guide discussions with manufacturers; equally, these discussions have led to improvements in the plan.

For planning purposes, it is presumed that a maximum of 10 pounds of material is to be injected per foot of travel of a 48-inch ripper tooth. Spacing is assumed to be 48 inches as well so that each pass would affect a 4-ft by 4-ft cross section. The 10 lbs per foot number is based on the experimental injection rates that were achieved in the laboratory, 0.5 to 4.5 lbs per foot for a 12-inch tooth, and also on a calculation of material placed per acre. At ten pounds per foot, each acre would receive 54.5 tons of material. While maximum injection rates are not known, this total would test that bound. Inasmuch as voids — a volume — are being filled, the mass, measured as a weight, of material injected will become less with any reduction in specific gravity. Consequently, dry material may be preferable to wet.

Experience with existing subsoilers that are 48 inches deep suggest that track-type tractors similar to a Caterpillar D9 or larger will be needed to draw the injection system. Speeds for these tractors (D9, D10, D11), when in first gear, range from 0 to 2.5 miles per hour with draw-bar pull decreasing inversely from the maximum available to zero at the top speed. Consequently, planning will be based on an average speed of one mile per hour.

BASIC COMPONENTS OF PROTOTYPE SYSTEM

There are four principal components within the injection system: (1) hopper/material storage bin, (2) feeder, (3) compressor, (4) injector/subsoiler. A conceptual drawing of the complete system is shown in Figure 3. Design questions include sizing sufficient for the task, ruggedness and mechanical simplicity, and location on the tractor or on a separate wagon. Some of these questions can be answered in advance and some, such as ruggedness and design simplicity will be deferred until or when a prototype is built.

Power for some of the moving parts of this system will need to come from the tractor. It is presumed that a power take-off will drive an hydraulic pump that in turn will drive feeders and augers. The blower may require a separate motor.

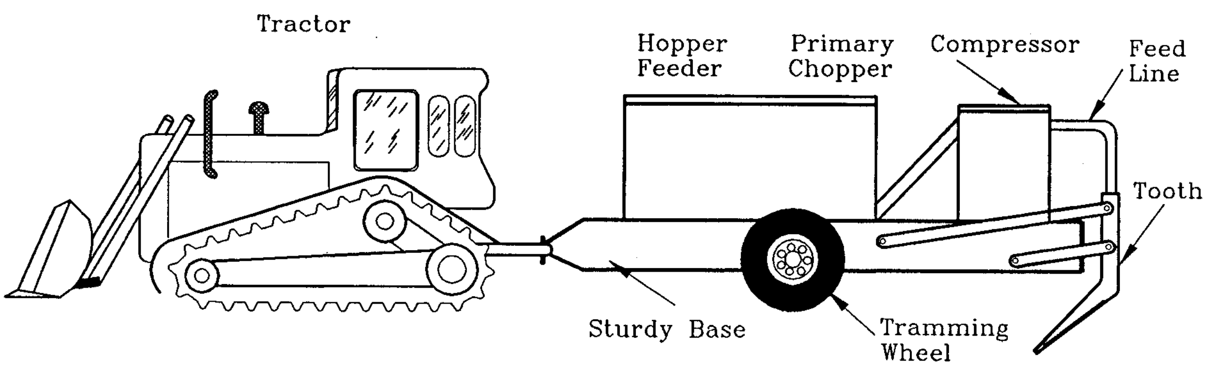
The least-capacity component will determine the maximum output of the system. Whether a feeder or a valve or whatever, all components will need to have the same throughput. Should that productivity be less than desired because of non-availability of larger components, then system speed or output or both will have to be reduced.

To avoid immediate recompaction, it is suggested that the material handling system be located between the tractor and the subsoiler. This implies either (1) a train of tractor, wagon to carry the material handling system, and subsoiler or (2) constructing the handling system on the frame of the subsoiler itself. For field flexibility, the total length of the system should be kept as short as possible.

Material Hopper. The design criteria for the hopper are size, delivery system, and material reduction (chopping) system. In addition, consideration is given to hopper location and method of filling it.

The hopper should be as large as possible so as to minimize refilling frequency. However, too large of a hopper will be unwieldy and unable to be filled from mobile haulage units. At ten pounds per foot, one ton will be expended in 200 feet, which is slightly less than one side of a square acre. From the standpoint of reloading, the hopper should not be less than one-ton capacity. If the waste product is loose, already chopped or otherwise unconsolidated, the hopper can be a trough with a chain-conveyor or auger feeder in the bottom. Such hoppers, similar to feed trucks or to ANFO powder trucks, can be ten tons in capacity or more. If the waste

Figure 3. Conceptual drawing of complete ripping and material injection system.



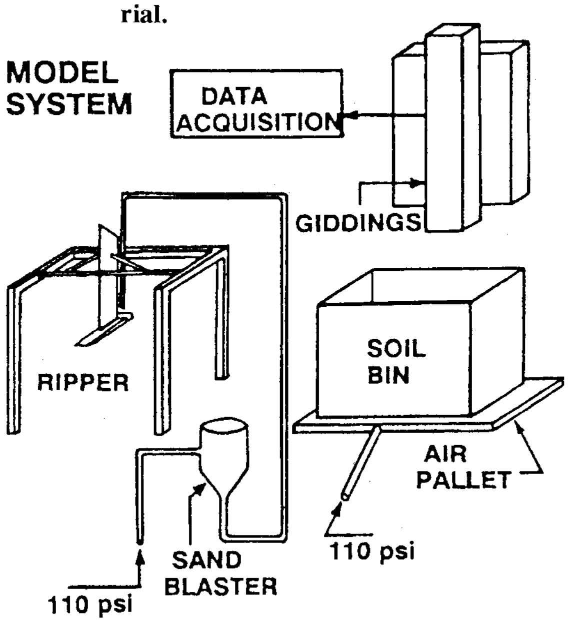
product is consolidated, for example round straw bales, then the hopper will need to be shaped so as to receive the product efficiently. An example of this is the round bale feeder, manufactured by Farmhand, Inc., which is also round and has a chopper built in.

Feeder. A delivery system will be needed to take material from the bottom of the hopper to the size reducer and then from the reducer to the pressurization system. At maximum capacity (ten pounds per foot and one mile per hour), the system will need to deliver 880 lbs per minute. As mentioned, a mechanical feeder will take material from the bottom of the hopper to the size reducer. If the reducer sits on top of the pressurization chamber, then it in turn will be fed by gravity.

Because of their ready availability and their ability to elevate material, it is suggested that an auger be tried as the mechanical feeder in the first instance. It is conceivable that a chopping blade could be fitted to the end of the auger so as to create a compact and enclosed size reducer. A schematic drawing of the proposed feeder system is presented in Figure 4.

Pressurization System. Injection will require the waste material to be fed into a pressurized stream of air at the design rate of 880 lbs per minute. In low-capacity systems, solids can be introduced directly into the air stream at the throat of a Bernoulli valve. A restriction in the air stream leaves a negative-pressure (Bernoulli effect) zone at walls of the tube just beyond the restriction. If material is introduced into this negative-pressure zone, it will be picked up by the flowing air stream. Higher capacity systems require some form of air lock such as a rotating star valve to get material into the air stream.

Figure 4. Schematic diagram of feeder system for pneumatic entrainment of organic material.



In either case, a blower is needed to provide the air stream. At ten pounds per foot or 880 pounds per minute, approximately 16 cubic feet of material will need to be delivered per minute. If the air stream were ten percent solids by volume, the compressor would need to deliver 160 cfm.

It is presumed that the blower and inlet valve will be directly under the end of the auger and will feed into a short length of flexible reinforced hose that will go directly to the ripper shank. To reduce the advent of hose failure from particle abrasion all curves will be as large a radius as possible. If possible, curves will be built from high-abrasion resistance material. For safety sake, an outer covering should be provided to protect equipment operators from hose failures.

Subsoiler. Existing subsoiling technology can be adapted to the air injection system. It is proposed to use a curved shank with a winged foot of dimensions that have been seen to be effective in other deep tillage trials. The injection tube will go down the back of the shank where it will be protected from abrasion. If possible, it will be divided into two branches with each branch leading to an exit on the trailing edge of each wing. It is hoped that this division of the flow path will encourage more material into the crescent failure zone and less into the slot cut by the shank. The laboratory tests described earlier show clearly that some material can be expected into the crescent zone. However, they also showed that, without special arrangements, most of the injected material will end up in the vertical slot.

To reduce internal friction and the chance of material build-up, all tube joints will be internally flush. It is expected that a tube in the order of two inches diameter will deliver the material to the foot. Each branch within the foot should have half the cross-sectional area of the main tube; this means that exit diameters would be 1.414 in.

In the first instance, tubes will be attached to the back of the ripper shank and foot (see Figure 5). Should first trials indicate the possibility of success, designs will be created for incorporating the tube within the shank and the foot.

VERIFICATION TRIALS FOR PROTOTYPE INJECTION SYSTEM

When a prototype injection system is built, it will be necessary to run a series of organized trials to (1) test the system, (2) verify the production rates that were assumed for the design, and (3) optimize the design of the subsoiler and its injection ports. While much of the system can be tested in the fabrication shop, the actual deposition of material can be tested only in field trials. Recognizing that there would be any number of frustrations associated with inaugurating a new system, the tests recommended here are for a working prototype that has had the initial faults worked out.

Field trials will be needed merely to determine methods of refilling the hopper while in motion. As these trials are underway, it will be possible to measure deposition rates and compare them with the design capacity. If less than the design rate is found, it will be necessary to diagnose the constraint: machinery or subsoiler-soil interface. An appropriate step will be to dig out a portion of the disturbed zone to see clearly the distribution of the injected material.

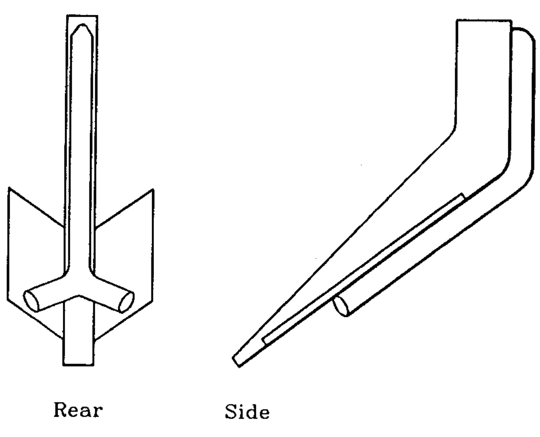
Each trial, therefore, should monitor continuously speed of the tractor and feed rates through the injector. Delays and their causes should be noted. Confirming measurements should be taken such as length of ripped zone and total amount of material injected. Additionally, turn times at the end of a row should be measured and time to refill the hopper should be measured.

CONCLUSION

Alternative soil reconstruction methods may serve to minimize the problem of compaction but may not eliminate it entirely. The practice of deep tillage is gaining support as a means of alleviating compaction. However, there is concern that the effects of deep tillage may be lost before the soil has the opportunity to develop a more natural structure. In response to this concern, there are some positive indications that recompaction can be minimized or eliminated through careful management practices and the injection of low-density soil amendments into the voids created by deep tillage.

Further development and field verification are required before this concept can be implemented. The economic feasibility of injection is another question that must be answered. If it is determined that the concept is sound technically but not practical from an economic standpoint, there may still be an application for this technology from a waste management perspective.

Figure 5. Detail of ripper shank with air injection nozzle.



ACKNOWLEDGEMENT

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Phosphorus Availability as Affected by Topsoil and Subsoil Mixing

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Abstract. The effect of topsoil and subsoil mixing associated with surface mining activities on P availability was investigated on a Sadler silt loam soil. Topsoil and subsoil mixtures were prepared, mixed with different P rates and subjected to wetting and drying cycles. Available P decreased due to wetting and drying. The decrease was a function of the proportion of subsoil in the mixture as well as P rates applied. Sorption of P increased as the subsoil content in the mixture increased. Higher P sorption was observed with highly acidic subsoil materials. These observations call for careful selection of soil materials for soil reconstruction, as well as soil handling techniques that minimize mixing of different soil strata at several stages of surface mining operations.

INTRODUCTION

Mixing of topsoil with underlying subsoil horizons is likely to occur during the soil removal in preparation for surface mining. This mixing may become more uniform during the stock-piling and soil reconstruction phases of mining operations. Topsoil properties may be significantly modified depending on the physical, mineralogical, and chemical properties of the subsurface soil. Various reports have indicated the wide variability in physical and chemical properties within soil units associated with post mine land as compared to natural undisturbed soils. Mixing of less desirable soil horizons as well as excessive soil compaction during soil removal and reconstruction may result in degradation of physical and chemical properties of restored soils (Jansen et al., 1985; Barnhisel, 1988). These limitations often result in poor root penetration, low available water, and consequently poor plant growth.

Although such mixing may be beneficial where the individual horizons of natural soils have sandy or heavy clay textures, have become compacted and/or have a clay or fragipan, or where the subsoil surface is acidic, detrimental effects have been reported by a number of researchers (Larsen et al., 1965; Barnhisel, 1988). The decrease in organic matter content following such topsoil and subsoil mixing is often closely linked with the N and P deficiencies characteristic of post mine soils. In greenhouse experiments using various soil horizons (Dancer and Jansen, 1981), better crop yields were obtained on topsoil (A horizon) than on B2 horizon material. Yields were lowest on acid clay pan subsoil. Forage yields decreased as the proportion of the B2 horizon material in topsoil increased. Replacing subsoil and topsoil in separate layers over spoil material has often been found to be superior to mixing them (Dancer and Jansen, 1981; Jansen and Dunker, 1985).

Severe nutrient deficiencies have been observed on reconstructed soils. In particular, P has been stressed as a key factor limiting successful revegetation of disturbed lands. It has long been recognized that only a small proportion of the added P fertilizer is absorbed by the plant and the remainder fixed in soil in various relatively insoluble forms. Theories have been advanced to explain P fixation mechanisms and factors affecting this phenomenon (White, 1980; Fixen and Grove, 1990).

Previous studies have indicated a general increase in P fixation with increasing clay content, surface area of clay, and Al for Si substitution in the mineral structure. Close positive relationships have been found between the $CaCO_3$, Fe, and Al hydrous oxide content in soil and P fixation capacity (Thomas and Peaslee, 1973). Beckwith (1965) observed that some subsoils exhibit a higher P retention than surface horizons and suggested that practices leading to mixing of such subsoil with topsoil should be avoided. Weir and Soper (1963) found a high positive correlation between P sorption and organic matter content which they attributed to Fe and Al associated with organic matter. In a review on P fixation, Velayuthan (1980) indicated that P fixation is enhanced by the presence of moisture. Many workers have also noticed that P retention proceeds rapidly in the initial stages, but a slower reaction continues for many weeks (Yuan et al., 1960; Larsen et al., 1965; Taylor and Ellis, 1978).

The various forms of soil P can be determined by fractionation procedures such as one developed by

Chang and Jackson (1957). Such studies indicate the relative amounts of P to be a function of the degree of weathering as well as parent material (Thomas and Peaslee, 1973). According to Yuan et al. (1960), over 80% of the added P was retained by soil as Al and Fe phosphates. Prolonged wetting and drying reduced the percentage of P in the Al-P fraction and increased that of the Fe-P form.

While many of these studies have been conducted on natural undisturbed soils, much still needs to be done to understand the behavior of P in disturbed soils. The objective of this study was to investigate the effect that topsoil and subsoil mixing during coal mining operations could have on P availability.

MATERIALS AND METHODS

Topsoil (TS, 0-15 cm) and subsoil (SS1, 20-40 cm) samples from a Sadler silt loam (fine-silty, mixed, mesic Glossic Fragiudalfs) on a previously limed, undisturbed site in Ohio County, western Kentucky, were air dried and ground to pass a 2 mm sieve. Topsoil had a silt loam to loam texture, and subsoil, silt loam.

Mixtures were prepared by mixing the two to make up 0, 25, 50, 75 and 100% subsoil (%SS). Three, one kilogram samples of each soil mixture were weighed out, and mixed thoroughly with 50, 100, and 150 mg of finely ground monocalcium phosphate. Using polyethylene bags to avoid any leaching, the samples were placed into pots and moistened to field capacity (30% moisture by weight) with deionized water. They were allowed to dry to wilting point (10% moisture) under greenhouse conditions. The pots were rotated during the drying process to minimize local effects due to difference in positions on the benches.

Designed to simulate field conditions, the wetting and drying process was continued for eight cycles, each cycle lasting nine days on average. At the end of each two cycles, 100 grams were sampled from each topsoil-subsoil mixture for analysis.

It was thought that P fixation would be even higher if the subsoil used was more acidic than SS1. To test this possibility, the experiment was repeated using the same topsoil, TS, but with a subsoil (SS2) of pH_w 4.5. Subsoil, SS2, was collected from the Bt horizon of an unlimed Sadler silt loam soil.

Available P in soil at different cycle times was determined by the Bray and Kurtz (1945) and Mehlich III (Mehlich, 1984) methods. Phosphorus fractionation was performed according to the Chang and Jackson (1957) procedure. Exchangeable bases and cation exchange capacity (CEC) were determined by the neutral 1N NH_4OAc method. Organic matter content (% OM) was determined by ignition and texture by the pipette method. Statistical analyses were performed using standard statistical procedures.

RESULTS AND DISCUSSION

Table 1 summarizes the chemical characteristics for the individual soil samples prior to mixing. Topsoil had slightly higher values for exchangeable Ca, and Na, and Bray 1 extractable P, but lower exchangeable K and Mg than SS1. Topsoil had higher % OM and CEC than SS1, but pH_w was closely similar. Compared to TS and SS1, SS2 had a lower pH, % OM, exchangeable Ca, CEC, and Bray 1 extractable P, although exchangeable Mg, K, and Na were higher in TS and SS1.

Effect of Wetting and Drying

Changes in available P during the wetting and drying process are presented in table 2 and plotted in figures 1, 2, and 3. It is clear that wetting and drying decreased available P significantly in all the soil mixtures, particularly during the first two cycles. Much higher reductions in available P were observed with a more acidic medium (Figure 3), but the trend essentially remained the same. For each soil mixture there was an overall increase in pH at the end of the wetting and drying process, particularly with the more acidic subsoil. This observation may seem to indicate ligand exchange of phosphate for surface aquo and hydroxy groups bonded to Al and Fe (Fixen and Grove, 1990) as the mechanism for P sorption.

Effect of Subsoil Mixing on Topsoil Properties

Table 3 presents a summary of the analysis of variance for the different variables measured. A significant linear response in available P (P<.01) was observed due to differences in mixtures (Figure 4). Increasing the

Table 1. Soil chemical characteristics prior to mixing.

Soil	pH_W	O.M	Exchangeable bases					
			Ca	Mg	K	Na	CEC	Bray 1P
		%	(cmol/kg)					(mg/kg)
TS	6.9	3.07	7.96	0.92	0.367	0.062	15.2	9.3
SS1	7.1	1.37	7.50	1.28	0.443	0.051	10.9	5.2
SS2	4.5	0.89	2.00	1.90	0.469	0.075	10.0	3.2

proportion of subsoil in topsoil was accompanied by a progressive decrease in available P during the entire time of the experiment. The effect was even greater in soil mixtures where a highly acidic subsoil medium was introduced. Figure 4 indicates that introducing 25% of such a medium into the topsoil caused an almost 50% decrease in available P in the topsoil. Similar implications can be derived from figure 3.

The decrease in available P (P applied minus extractable P) at a given time of the experiment was used

Table 2. Variation in mean available P for the five soil mixtures during wetting and drying cycles[a]

Cycles:	0	2	4	6	8
%SS			*Bray 1 P (mg/kg)*		
0	20.16	15.94	16.16	15.51	16.01
25	18.53	13.74	13.33	13.26	13.62
50	16.58	9.85	10.96	10.18	10.16
75	13.71	8.44	7.78	8.01	8.69
100	10.89	4.82	4.00	5.37	4.63
			Mehlich III P (mg/kg)		
0	27.99	21.16	19.49	20.65	19.66
25	25.33	18.33	18.01	16.67	16.85
50	22.34	14.49	11.65	14.33	11.83
75	20.16	12.68	11.83	12.83	11.83
100	17.17	9.66	8.66	10.02	8.84
			Bray 1 P (mg/kg) using SS2		
0	20.16	ND	16.16	ND	16.01
25	9.27	ND	7.95	ND	8.05
50	6.78	ND	5.47	ND	5.70
75	4.40	ND	3.05	ND	3.44
100	2.11	ND	1.20	ND	1.36

[a] Averaged over the three P rates.

ND Phosphorus was not determined at these wetting and drying cycles.

Figure 1. Variation in Bray 1P due to wetting and drying of the various mixtures using a non acidic subsoil (SS-1). Data averaged over three P rates.

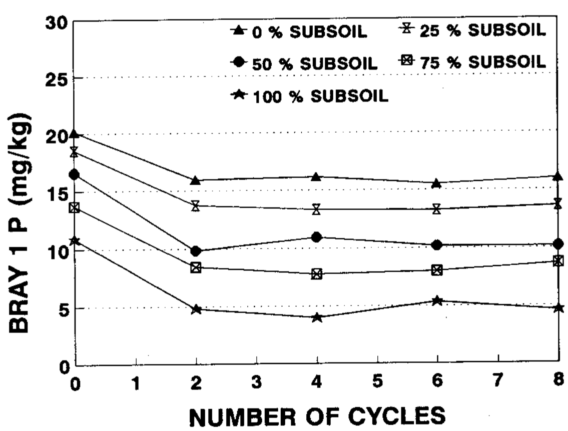


Figure 2. Variation in Mehlich III P due to wetting and drying of the various mixtures. Data averaged over three P rates.

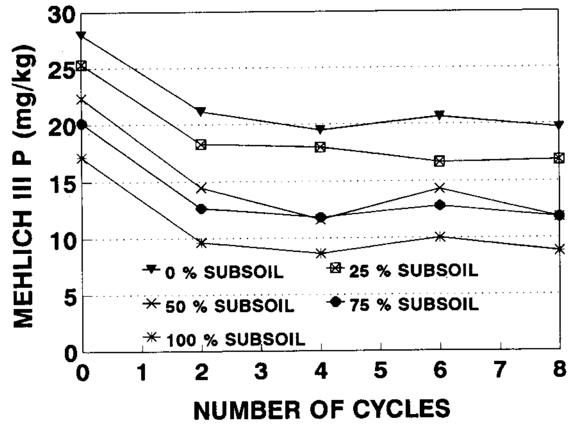


Figure 3. Variation in Bray 1P due to wetting and drying of the various mixtures using an acidic subsoil (SS-2). Data averaged over three P rates.

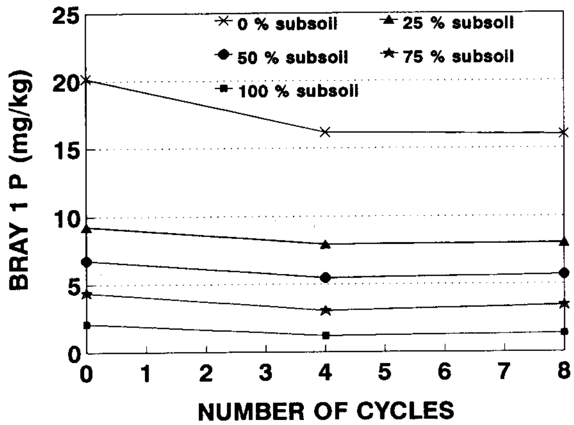
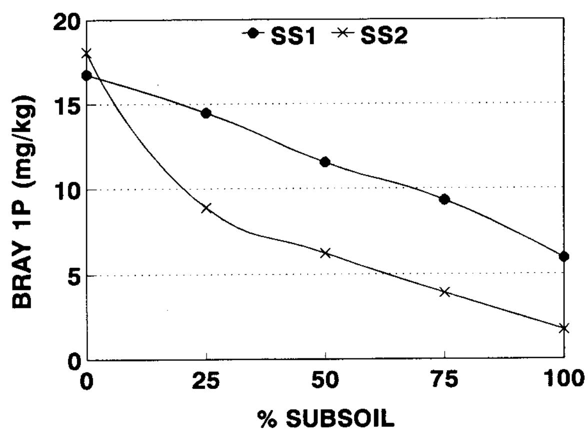


Figure 4. Available P as affected by topsoil and subsoil mixing. Data averaged over three P rates and eight wetting and drying cycles.



to estimate the amount of P sorbed (Velayuthan, 1980). Tables 3 and 4 indicate that P sorption varied significantly (P<.01) as a function of the proportion of subsoil in the mixture. Higher P sorption values were again obtained where a more acidic subsoil medium was used (Table 4). These results relate closely with Beckwith's (1965) earlier observations of the higher P fixation capacity exhibited by some subsoils. The effect of subsoil on topsoil properties is further indicated by the significant drop (P<.01) in topsoil pH observed with increasing proportion of SS2 in the mixture (r=0.985**).

A significant linear (P<.01) relationship between sorbed P and P rates applied was also observed (Table 3). For the ranges of P applied, results indicated an increase in amount of P sorbed with increasing amount of P added (r=0.770** for SS1), particularly in mixtures with high subsoil content, and more so for SS2 (r=0.990**).

Results also indicated an increase in the proportion of Al-P and Fe-P forms, but a decrease in Ca-P, although these were not significant. It is possible that the time period for which the experiment proceeded was not long enough to realize any significant changes in the P fractions observed by Yuan et al., (1960).

CONCLUSION

The results of this study clearly demonstrate the effect on P availability that may result from the possible mixing of different soil strata during soil removal, stock-piling, replacement, and levelling operations associated with surface mining. Phosphorus availability was significantly reduced with an increase in subsoil content in the mixture. The results suggest a higher P fixation in cases where highly acidic subsoil materials are mixed with topsoil. Owing to the less desirable characteristics that some soil media may potentially possess, soil restoration processes ought to consider careful selection of suitable soil materials for use, as well as material handling procedures that minimize mixing of different strata.

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Table 3. Summary of the analysis of variance

		Bray P	Mehl. P	Sorb.# P	Bray P	Mehl. P	Sorb.# P	pH_w
		SS1			SS2			
Source	df	(F ratio)						
M	4	38.0**	16.1**	37.8**	88.6**	2.7+	87.2**	181**
P	2	18.2**	13.1**	7964**	2.4	0.8	8812**	0.1
M*P	8	0.3	0.4	0.3	0.9	1.1	0.8	0.1
Mlin	1	151**	63.0**	150**	312**	9.7**	306**	716**
Mquad	1	0.3	0.4	0.3	32.0**	0.1	33.4**	5.1*
Plin	1	35.8**	26.2**	5928**	8.7*	0.6	17623**	0.1
Pquad	1	0.7	0.1	0.6	0.1	1.1	0.1	0.1
R^2		0.76	0.61	0.99	0.96	0.58	0.99	0.98
C.V.		23.0	25.9	23.0	21.3	42.3	1.8	2.2

** P<.01, * P<.05, + P<.10

Sorbed P based on Bray 1 extractable P.

Table 4. Sorbed P as affected by Topsoil and Subsoil mixing[a]

%SS	Sorbed P (SS1) (Bray 1)	Sorbed P (SS1) (Mehl.III)	Sorbed P (SS2) (Bray 1)	Sorbed P (SS2) (Mehl.III)
0	83.2	78.2	81.9	77.0
25	85.5*	81.0+	91.0**	87.8
50	88.5**	85.1**	93.8**	87.5
75	90.7**	86.1**	96.1**	112.0**
100	94.1**	89.1**	98.1**	97.8+

** P<.01, * P<.05, + P<.10.

[a] Averaged across three P rates and eight cycles

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Utilization of Lime-Stabilized Fly Ash Scrubber Sludge in Surface Mine Reclamation: Results of a Preliminary Investigation

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Abstract. A three-year study was conducted to investigate the suitability of a mixture of fly ash and flue gas desulfurization sludge, termed fly ash scrubber sludge (FASS), for use in surface mine reclamation practices. Four major objectives were addressed: 1) characterization of lime-stabilized fly ash scrubber sludge physical and chemical properties, and their temporal variability; 2) effects of fly ash scrubber sludge on soil properties; 3) effects of soil/fly ash scrubber sludge mixtures on crop plants; 4) development of recommendations for utilization of fly ash scrubber sludge in surface mine reclamation practices.

Elemental data for FASS were divided into three categories: major elements (Al, Ca, Cl, Fe, K, Mg, and Na), comprising greater than 0.1% of the total weight; minor elements (B, Mn, Pb, and Zn), present in amounts between 100 mg/kg and 0.1%; and trace elements (As, Ba, Co, Cr, Cu, Ni, Se, and Sr), present at concentrations less than 100 mg/kg.

Lysimeter studies were used to determine the feasibility of near surface disposal of fly ash scrubber sludge in reclamation and evaluated its potential as a soil amendment for forage and row crops. Primary effects on crop plants were caused by elevated soil B levels.

Incorporation of 15% FASS in the surface soil induced fatal B toxicity in soybeans (Glycine max L.) and a 22% reduction in alfalfa (Medicago sativa L.) forage yield in 1989. Additional treatments included: a) 50% FASS mixed with glacial till subsoil, and b) 100% fly ash scrubber sludge located below a 30 cm topsoil layer. Fly ash scrubber sludge added below the topsoil reduced soybean grain and alfalfa forage yields by 81% and 48%, respectively. Severe B toxicity symptoms occurred, and the grain and forages produced were unuseable. Toxicity symptoms increased during periods of low rainfall, and subsided with favorable soil moisture conditions. Leaching and weathering resulted in markedly reduced toxicity symptoms in 1990.

INTRODUCTION

Associated Electric Cooperative, Inc. (AECI) is a major energy producer and electrical distributor for rural Missouri. The company's boilers burn from 60 to 200 tons of coal per hour. One unit, equipped with a scrubber, generates about 875,000 tons of combined fly ash scrubber sludge (FASS) per year. Projected FASS production for each of the next five years exceeds 1,000,000 tons.

Conventional by-product handling technology consists of holding this waste in unlined ponds or landfills (Francis et al., 1985). Costs associated with lining ponds are quite large. Both fly ash and scrubber sludge contain significant quantities of trace elements, and increased use of lined ponds may be required in the future. Combustion by-products have few beneficial uses in the United States, and FASS utilization remains unreported.

Since AECI operates a number of coal burning power plants, and projections of future power generation predict continued reliance on coal burning, tremendous amounts of FASS will be generated. Disposal is an environmental and economic concern which will become increasingly important as residue production increases. Land application of power plant wastes could result in substantial financial savings to utilities and their consumers. Preliminary analyses of AECI FASS indicated the presence of agriculturally important trace elements. Since FASS also contains high Ca levels, important agriculture fertilizer benefits may result from its incorporation into soils.

This investigation concerns an alternative method of dealing with FASS by incorporation into agricultural

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soils, in minespoil reclamation and in near-surface disposal situations. Agricultural usage of FASS may offer a reasonable alternative means of handling to the coal-based electric power producers, particularly when compared to costs which would be increased when, and if, ash/sludge storage ponds and landfills are required to be lined.

Investigations into the characterization and utilization of FASS are sparse. The objectives of this study are: 1) to determine the physical and chemical composition of AECI power plant wastes; 2) to predict the effects of FASS on crops when used as a soil amendment; and 3) to make some specific recommendations for land-application of FASS on reclaimed soils associated with the Thomas Hill mining operation.

EXPERIMENTAL METHODS

Fly ash scrubber sludge FASS temporal variability samples were collected from the Associated Electric Cooperative, Inc. (AECI) power plant at Thomas Hill, Missouri approximately every three months from May, 1988 through March, 1991. Ten samples weighing approximately 5 kg each, chosen to represent the range of physical properties of materials present in FASS stockpiles, were collected on each sample date. Samples were chosen to represent the range of aggregate morphology, color and water content characteristics of materials in the stockpiles on a given date. Reaction, $CaCO_3$ equivalents (CCE), and elemental analyses were performed with standard methods (Wendell, 1992). Calcium carbonate equivalents were determined using 0.02 N HCL decomposition and a H_2O mannometer to measure CO_2 evolution. Boron was extracted with $CaCl_2$-mannitol and determined colorimetrically by the azomethine-H method (Bingham, 1982). Chloride was determined by HNO_3 extraction and Cl-specific electrode. All other elemental analyses were by atomic absorption spectrophotometry or atomic emission spectrophotometry.

Analysis of variance was performed on chemical data to determine temporal variability of FASS properties. Chemical properties measured were treated as independent variables. Sampling dates were treated as individual treatments. The total sample set from all dates was considered the experimental sampling population.

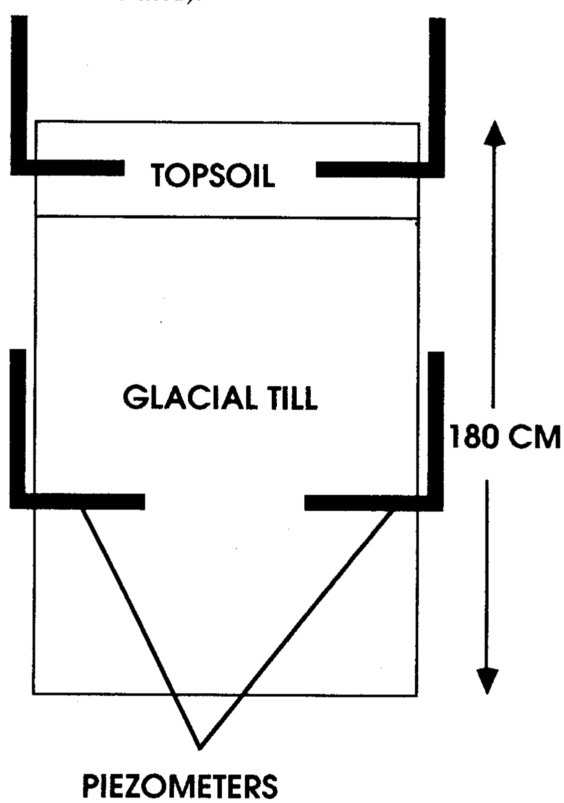
Lysimeters were constructed at the UMC Bradford Experimental Farm during the summer of 1988. Reclamation materials included topsoil, glacial till or subsoil, and FASS. Above-ground lysimeters (Fig 1.) 1.8 m deep by 1.2 m diameter were constructed from ribbed, spiral wrapped PVC pipe placed on a base consisting of white gravel over 5-cm rock. A 0.9 mm thick plastic floor was stapled and glued to the bottom of each lysimeter to prevent water leakage. Materials were loaded into lysimeters with a bucket-loader. After every two or three buckets loaded, soils were packed as tightly as practical using hand shovels and a sharpshooter. Soil layers were scarified with a shovel to minimize H_2O perching between layers of contrasting textures.

Piezometers (Burk et al., 1988) and Soiltest™ nylon moisture cells (Soilmoisture Equipment Corp., Santa Barbara, Calif.) were installed at the center of each layer of soil as the lysimeters were filled.
Four combinations of soil and FASS materials were distributed among twelve lysimeters:

Treatment #1.
Control (no FASS).
- 30 cm topsoil.
- 150 cm subsoil/glacial till overburden.

Treatment #2.
Fly ash scrubber sludge incorporated as a soil amendment into the subsoil/ glacial till overburden material.
- 30 cm topsoil.
- 90 cm 50% subsoil/50% FASS mixture.
- 60 cm subsoil/glacial till overburden.

Figure 1. Lysimeter design (control treatment illustrated).



Treatment #3.
Fly ash scrubber sludge between topsoil and subsoil/ glacial till overburden layers.

- 30 cm topsoil.
- 90 cm FASS.
- 60 cm subsoil/glacial till overburden.

Treatment #4.
Fly ash scrubber sludge as a topsoil amendment.

- 30 cm 85% topsoil/15% FASS mixture.
- 150 cm subsoil/glacial till overburden.

The treatments were in an orthogonal statistical design. Lysimeters were arranged into six sets of two lysimeters each. Three sets of lysimeters were packed as described for Treatment #4 and each of the three remaining treatments was assigned to one lysimeter set. This design allowed more intensive study of Treatment #4 which used FASS as a micronutrient source and soil amendment. The 15% FASS/topsoil ratio incorporated the minimum FASS amount practical in surface mine rèclamation.

One lysimeter from each set was seeded with 'Great Plains Cimmarron' alfalfa (*Medicago sativa* L.) and the other to Williams 82' soybeans (*Glycine max* L.) in spring 1989 and 1990.

Crops were periodically sampled during the growing season and harvested when mature for analysis of micronutrient status, evidence of heavy metal, B and salt toxicities, and suitability as food or forage. Plants were harvested by cutting at soil level. Soil particles were removed by washing in de-ionized water. Plants were oven-dried at 55ºC. Leaves were separated from stems for analysis. Arsenic, B, Ca, Cl, Fe, K, Mg, Na, Se, and Zn were analyzed by the same procedures as used for FASS analysis. Forage and grain yields (Kg Ha^{-1})were determined from the final harvest of each crop.

RESULTS AND DISCUSSION

Reaction

The materials investigated were moderately to strongly alkaline. Mean reaction values for the entire data set were pH(H2O) = 8.74 and pH(s) = 8.43 (Table 1). The data agree with those of previous investigations (Nebgen et al., 1980; Kurgan et al., 1984). Significant within-treatment variability was not detected. Mean sampling date coefficients of variability were approximately 5.4% Analysis of variance ($p = 0.05$) revealed significant differences between treatment (sampling date) means and the experimental (total data set) mean. The experimental mean was representative of the population, but a few outliers were in the neutral and very strongly alkaline categories. Reaction values were above pH(s) = 8.5 for many samples indicating that CaO controls pH in much of the FASS (Lindsay, 1979).

The pH component is probably the most important variable in any FASS utilization scheme because reaction controls the solubility, mobility, and physiological availability of most plant-available elements.

An important objective in utilization of power plant wastes is to raise the pH of acid soils, thus creating a more favorable rooting environment (Taylor and Schuman, 1988). Fly ash amendments have been shown to raise the pH of acid mine soils (Spooner et al., 1981; Taylor and Schuman, 1988). Fly ash was added to acid soils. An initial rise in soil pH to desired levels of pH 6.5 to 7.0 was followed by a pH decrease to original values as the neutralizing capacity of the ash was depleted. Reduction in pH takes place more quickly in soils with poor buffering capacities. To maintain near-neutral reaction, periodic application of additional fly ash was recommended, provided heavy metals did not accumulate to unacceptable levels.

Calcium Carbonate Equivalents

Pulverized, high-grade limestone injected into the flue gas stream during the desulfurization process is the principal source of Ca in FASS. Calcium in FASS occurs primarily as gypsum (CaSO4.2H2O) or anhydrite (CaSO4) produced as sulfur is scrubbed from flue gasses, or as unreacted CaCO3 and CaO, a by-product of superheated CaCO3.

The mean CCE content of the entire sample population was 11.3% (Table 1). Variability is attributed to three factors: 1) lack of control in the "manufacturing process" in which fly ash is mixed with flue gas desulfurization sludge; 2) weathering, dilution and contamination caused by heterogeneous exposure to precipitation while in the stockpiles; and 3) contamination with other materials such as bottom ash, refuse, etc. during stockpiling. Individual data points were scattered, but mean values obtained for the total sample population are consistent with the the lower end of 10% to 20% CCE content range reported for unweathered fly ash from various sources (Page et al., 1979).

Table 1. Fly ash scrubber sludge reaction and $CaCO_3$ equivalents. Summary for all samples.

	mean	std dev.	c.v.%	min.	max.
pH(H_2O)	8.7	0.6	6	7.2	10.8
pH(s)	8.4	0.6	6	6.8	10.1
$CaCO_3$(%)	11.3	4.7	38	0.5	23.1

Calcium carbonate equivalent content alone underestimates the liming ability of FASS. Injection of $CaCO_3$ into hot flue gasses during the scrubber process results in conversion of some of this material into CaO. Calcium oxide was not quantified in this experiment, but appeared to exist in amounts sufficient to control pH in approximately one - third FASS samples.

The CCE data of FASS reveal the inefficiencies of current scrubber technology. In an ideal situation, all $CaCO_3$ injected into the flue gas stream would be consumed by reaction with SO_4 on a one to one basis, producing one mole of gypsum ($CaSO_4$.H2O) or anhydrite ($CaSO_4$) per mole $CaCO_3$. Current processes introduce $CaCO_3$ in large excess, much of which remains unreacted. This is evidenced by the mean 11.3% CCE content observed in Thomas Hill FASS. Decomposition of CaCO3 into CaO is an undesired reaction pathway. Some investigators (Kurgan et al.,1984; Nebgen et al., 1980) have estimated that $CaSO_4$.H2O and $CaSO_4$ comprise by weight only about 4.0% of flue gas desulfurization sludge. Future technology may increase efficiency by recycling either pulverized limestone or FASS itself into the flue gas stream, thereby reducing resources consumed and solid wastes produced.

Major Elements

Major elements (Al, Ca, Cl, Fe, K, Mg, and Na) comprise greater than 0.1 weight percent of the combustion by-product (Table 2). Calcium was the most abundant element, comprising greater than 10% of many FASS samples. Calcium in FASS occurs as silt-sized, free carbonate, sulfate, and oxide accumulations (Sharma et al., 1989), and $CaCl_2$ is a probable component. Calcium concentrations in individual samples varied from 2.9% to 31.8%. The data corroborate Hodgson et al., (1982) who recommended amending acid soils with combustion by products rather than lime. However, neither Ca concentrations nor its speciation are controlled in the FASS manufacturing processes. Thus, temporal variability becomes a factor which limits the utility of FASS as a primary soil amendment (Wendell, 1992).

Table 2. Fly ash scrubber major elements. Summary for all samples.

element	mean	std dev	c.v.%	min.	max.
	- - - - - - -	- - - - - -	%	- - - - - -	- - - - - - -
Al	0.6	0.5	77	0.1	3.5
Ca	14.2	6.4	45	2.9	31.8
Cl	0.8	0.1	135	0.0	4.5
Fe	6.4	5.7	88	0.9	45.1
K	0.2	0.1	56	0.0	0.8
Mg	0.2	0.1	65	0.1	0.9
Na	0.2	0.1	63	0.0	0.5

Mean Al and Fe amounts were 0.6% and 6.4%, respectively. These metals probably occur as oxides and carboxides which are generally sequestered in the stable particle cores, rendering them largely unavailable to plants (Klein et al., 1975; Hansen and Fisher, 1980; Bache and Lisk, 1990). However, El Mogazi et al., (1988) reported that combustion by-products may serve as a slow-release source of core elements over long weathering periods. Magnesium, K, and Na existed in mean amounts of approximately 0.2 weight percent, and are considered too low to improve plant nutrient status. Magnesium and K exist in combustion by-products primarily as as free ions in association with Cl, or as carbonates (Matusiewicz and Natusch, 1980). Chloride is important because it occupies a dual role as both a micronutrient and phytotoxin, depending upon concentration (Marschner, 1988).

Sodium concentrations in this study were higher than commonly reported for fly ash (Kurgan et al., 1984) and indicate potential for soil salinity problems.

Initial variability of elemental concentrations in FASS is a function of concentration in the individual fly ash and scrubber sludge components and the ratios in which the components occur. Weathering, leaching and translocation subsequent to stockpiling further alter chemical composition. Weathering effects vary with solubility and mobility of individual elements.

Chloride levels varied greatly due to the high solubility and mobility of the Cl anion, varying amounts in coal seams, and with combustion conditions. The FASS stockpiles always contained fresh FASS as well as materials which had been exposed to the weathering and leaching influences for as long as four months. Thus one might expect to find materials with trace Cl amounts in close proximity with materials containing several percent Cl.

Minor Elements

Minor and trace elements in fly ash (Page et al., 1979) are sequestered in the smaller particle size classes, such as fine silt and clay. In general, FASS contained four elements including B, Mn, Pb, and Zn in minor element concentrations (Table 3). Boron, Mn and Zn are of particular interest because they are plant-essential micronutrients (Marschner, 1988). Analysis of variance revealed significant differences ($p=0.05$) between B and Zn treatment (sample date) means and the experimental means. Zinc was the most abundant minor element, with a mean of 402 mg/kg. However, Zn variance exceeded other minor elements. Fly ash scrubber sludge addition can significantly increase total soil

Zn, but associated alkalinity can decrease plant-available Zn (Schnappinger et al., 1975; Townsend and Hodgson, 1973), possibly inducing Zn deficiency. Theis and Wirth (1977) reported zero release of surface-available Zn from fly ash in alkaline solutions.

Boron in Thomas Hill FASS commonly occurred in concentrations hundreds of times greater than in most soils. Boron in FASS is sequestered predominantly in fly ash and occurs in substantial quantities on surfaces and interiors of silicate spheres and frits (Cox et al., 1978). Furr et al. (1977) reported a significant correlation ($r = 0.83$) between plant-available B and B in fly-ash amended soil. Boron is difficult to manage from a crop standpoint because a narrow range exists between deficient and toxic soil concentrations (Elseewi and Page, 1982). Crop plants normally tolerate from 5 to 15 mg/kg soil B, depending upon species. The toxicity threshold in leaf tissue is approximately 30 mg/kg for soybeans. Alfalfa and some other crops possess a larger B nutritional requirement, while others are extremely sensitive to B toxicity. Fly ash scrubber sludge appears to be an excellent slow-release B source, and may be useful in correcting deficiencies (Cox et al., 1978). Boron in its most readily available form occurs as boric acid ($B(OH)_3$-) in acid to neutral soils, but becomes less available and occurs increasingly as hydroxyborate ($B(OH)_4$) with increasing soil alkalinity (Keren and Bingham, 1985). Manganese in FASS occurs as oxides and carbonates. Alkalinity associated with FASS is expected to reduce Mn availability. However, Mn deficiencies associated with the use of combustion by-products have not been reported.

Table 3. Fly ash scrubber minor elements. Summary for all samples.

element	mean	std. dev.	c.v.%	min.	max.
	- - - - - - - - - - -	- - - - -	mg/kg	- - - - -	- - - - - -
B	280	184	66	6	974
Mn	189	101	53	37	863
Pb	242	93	39	0	421
Zn	402	345	61	50	999

Table 4. Fly ash scrubber trace elements. Summary for all samples.

element	mean	std. dev.	c.v.%	min.	max.
	- - - - - - - - - - -	- - - - -	mg/kg	- - - - -	- - - - - -
As	58.4	40.4	69	0.0	133.3
Ba	91.1	37.0	41	2.5	150.5
Co	12.8	6.6	38	0.3	36.8
Cr	23.1	10.5	45	2.8	53.4
Cu	46.7	37.5	80	0.0	249.1
Ni	69.9	43.0	64	3.5	319.1
Se	8.7	9.9	114	0.0	54.0
Sr	41.5	14.8	36	14.0	98.6

Lead in Thomas Hill materials occurred at a mean concentration of 242 mg/kg. These levels exceed those commonly reported even for undiluted fly ash (Los Alamos National Laboratory, 1976). Lead produces acute toxicity in humans and animals, but is immobile in most soil systems and is not taken up in significant amounts by plants. Lead compounds in alkaline systems are essentially insoluble.

Trace Elements

Eight trace elements in Thomas Hill FASS included As, Ba, Co, Cr, Cu, Ni, Se and Sr. Arsenic, Ba, Cu, Ni, and Sr are commonly reported as minor elements in fly ash investigations, which illustrates the diluting effect of mixing scrubber sludge with fly ash. Trace elements are concentrated on particle surfaces (Theis and Wirth, 1977).

Trace element mean concentrations except Se exceeded 10 mg/kg (Table 4). Variability was greatest in As, Cu, and Se. Coefficients of variability exceeded 100% for Se. Significant differences ($p = 0.05$) between treatment date means and the experimental means occurred for Co, Cu, Ni and Sr.

Copper is the only plant-essential trace element in FASS. Cobalt, Cu, and Se are essential in livestock and human nutrition, and Rhizobium spp.require Co for N_2-fixation. Trace elements in Thomas Hill FASS, with the exception of Co, occur at concentrations too low to correct micronutrient deficiencies.

Selenium is rarely toxic to plants, but can accumulate in grain and forages at concentrations toxic to livestock and humans. The mean Se concentration in FASS was 8.7 mg/kg. Selenium is chemically related to S, allowing selenate to compete with sulfate for carrier sites in plant roots (Mengel and Kirby, 1987). Plant Se uptake is determined by soil S:Se ratios. Flue gas desulfurization sludge has been reported to contain approximately 4.0% S (Kurgan et al., 1984). Large S:Se ratios inherent in FASS insure minimal Se enrichment in plant tissues. Soil Se concentrations will not be appreciably increased with incorporation of Thomas Hill materials.

Arsenic occurred in mean quantities of 58 mg/kg, and soil As in fly ash exists as non-toxic As(V), which is essentially immobile except under reduced (water-logged) conditions (Silberman and Harris, 1984). Arsenic accumulations are unlikely in plants grown in reclamation or agronomic soil systems.

Strontium is chemically similar to Ca, but does not replace Ca in plant physiological processes. Because Ca^{2+} restricts Sr^{2+} uptake (Reissig, 1962), liming effects associated with FASS in soils should result in suppressed plant tissue Sr concentrations.

Soil Properties

Topsoil materials used in the lysimeter experiments were moderately acid, with a mean pH(s) = 5.8 (Table 5). The glacial till subsoils were nearly neutral, with mean pH(s) = 7.2). Reaction values were more acidic than those from 15 cores obtained from a two year old dragline reclamation site near the Thomas Hill surface mine (R.D. Hammer, personal communication), revealing the temporal and spatial variability inherent in overburden materials. Fly ash scrubber sludge was moderately to strongly alkaline.

Addition of 15% FASS to topsoils effectively neutralized acidity, raising the mean bulk soil pH(s) from 5.8 to 7.5. This supports the hypothesis that FASS can serve as an effective liming material. Fifty percent FASS mixed with the glacial till subsoil raised the mean bulk soil pH from a state of near neutrality to one of mild alkalinity, with mean pH(s) = 8.0. Reaction of soil/FASS mixtures was not homogeneous. Ped or clod interiors retained their initial reaction after mixing, while zones of sharply higher pH occurred in FASS coatings surrounding the peds. Weathering and reaction of the FASS with soil materials should cause the boundary between the the relatively acidic ped interiors and alkaline exteriors to become more diffuse with time.

The mean $CaCO_3$ equivalent content (CCE) of the Thomas Hill topsoil materials used in the lysimeter experiment was only 0.1% (Table 5). Calcium carbonate content of the glacial till subsoil varied from 6.2 to 13.1%, and averaged 9.8%. Fly ash scrubber sludge from the lysimeters contained a mean 15.9% CaCO3, which approaches the maximum of the range for temporal variability samples (Table 1).

Addition of 15% FASS to topsoils raised the mean soil $CaCO_3$ content to 1.0%. Because of its small particle size and relatively large specific surface, much of the $CaCO_3$ in the FASS was probably rapidly consumed in reaction with soil acidity, quickly raising soil pH. Relatively little $CaCO_3$ remained in reserve. Soils high in reserve acidity probably require periodic additions of FASS to maintain soil reaction neutrality (Adams et al., 1970). Neutral to alkaline soils probably cannot be amended with fly ash more than once. Potential B toxicity may make repeated application of FASS to soils impractical.

Table 5. Chemical properties of lysimeter materials.

	topsoil	subsoil	topsoil/ FASS	subsoil/ FASS	FASS
pH(s)	5.8	7.2	7.5	7.9	8.4
$CaCO_3$%	0.1	9.8	1.0	14.2	15.9
EXCHANGEABLE cmol(c) kg^{-1}					
Ca	12.8	29.2	57.8	115.8	200.9
Mg	3.0	3.2	3.7	5.2	5.2
K	0.3	0.4	0.4	1.8	2.6
Na	0.1	0.2	2.2	4.1	4.4
TOTAL (mg/kg)					
B	5.5	4.4	127.7	232.9	227.9
Cl	67.2	120.4	3784.6	3303.5	5632.9

Exchangeable Ca, Mg, K and Na levels were consistent within materials. Relative abundance of exchangeable cation levels in all materials followed a pattern typical to most soils, with Ca>>Mg>K>Na.

Calcium dominated the exchangeable base content of all samples (Table 5). Mean exchangeable Ca was 12.8 cmole(c) kg^{-1} in the topsoil and 29.2 cmole(c) kg^{-1} in the glacial till. Fly ash scrubber sludge averaged 200.9 cmole(c) kg^{-1}. Fly ash scrubber sludge increased exchangeable Ca values in both soil materials by approximately 400%.

Mean exchangeable Mg was 3.0 cmole(c) kg^{-1} in the topsoil and 3.7 cmole(c) kg^{-1} in the glacial till. Fly ash scrubber sludge averaged 5.2 cmole(c) kg^{-1}. Incorporation of 15% FASS into the topsoil increased exchangeable Mg by about 25%. Fifty percent FASS added to the subsoil increased exchangeable Mg by approximately 64%. Fly ash scrubber sludge did not contain enough exchangeable Mg to be considered an adequate Mg fertilizer source.

Topsoil from the Thomas Hill site supplied insufficient K to meet most crop nutrient requirements. Mean exchangeable K was only 0.3 cmole(c) kg^{-1} in the topsoil and 0.4 cmole(c) kg^{-1} in the glacial till. Fly ash scrubber sludge averaged 2.6 cmole(c) kg^{-1}. Addition of 15% FASS into the topsoil increased exchangeable K by approximately 30%. Fifty percent FASS in the subsoil increased exchangeable K by approximately 400%. As with Mg, FASS did not contain enough exchangeable K to be considered an adequate K fertilizer source.

Exchangeable Na in Thomas Hill topsoils was low, averaging only 0.1 cmole(c) kg^{-1}. Mean subsoil levels were 0.2 cmole(c) kg^{-1}. Fly ash scrubber sludge averaged 4.4 cmole(c) kg^{-1}. Mixing 15% FASS into the topsoil increased exchangeable Na to approximately 2.2 cmole(c) kg^{-1}. Fifty percent FASS added to the subsoil increased mean exchangeable Na to 4.1 cmole(c) kg^{-1}. The potential for salt toxicities induced by addition of unweathered FASS to soils is a concern, but B toxicity is considered the main limitation to plant growth.

Boron and Cl have are potentially toxic micronutrients at elevated concentrations (Marschner, 1988). Potential effects of salt and especially B toxicities will be the principal detriments to crop growth in FASS-amended soils.

Plant/Lysimeter Results

Boron toxicity symptoms in in alfalfa are normally confined to older leaves and manifest themselves as a burning or necrosis of the leaf tips (Gupta at al., 1985). In 1989, alfalfa grown on lysimeters containing FASS began showing symptoms of B toxicity within days of emergence. Leaf tips attained a whitish coloration characteristic of severe B toxicity. With time, the necrosis progressed down the leaf margins and toward the midrib, eventually consuming the entire leaf. Boron toxicity symptoms were most severe during periods of low precipitation, when plants were experiencing drought stress. During extremely dry periods, plants dropped most of their leaves. Plants produced new flushes of leaves following major precipitation events, but B toxicity symptoms soon redeveloped. The 1989 growing season consisted of several cycles of growth following precipitation events, progressive B toxicity, and eventual leaf drop. Mortality claimed few alfalfa plants during the 1989 season. Plants grown on lysimeters with subsoil FASS were most affected by both the drought and B toxicity, and attained only about one third the height of the control plants. High salt and B concentrations in the subsurface restricted root growth to the upper 30 cm layer, which was quickly depleted of moisture. Roots growing in the topsoil/FASS interface encountered nearly lethal B concentrations. Plants growing in the 15/85 FASS/topsoil treatment showed less severe B toxicity symptoms and retained their leaves longer than those in the other treatments. This is attributed to alfalfa's ability to root deeply into the subsoil, obtaining much of its water and nutrient requirement from below the layer containing FASS. These plants usually maintained appearances similar to the control for several days following significant precipitation events.

Alfalfa forage was harvested for yield on 10/1/89. The control lysimeter produced 5965 kg/ha alfalfa hay (Table 6). Hay from the control lysimeter was visually determined to be of good quality. Yields from the two layered treatments were reduced from the control by approximately 48 percent. Mean yield from the FASS-amended topsoil treatment was 4652 kg/ha, approximately 23% less than the control. Forage harvested from the FASS-treated lysimeters was unuseable as food for livestock.

Table 6. Alfalfa forage yields from soils treated with fly ash scrubber sludge.

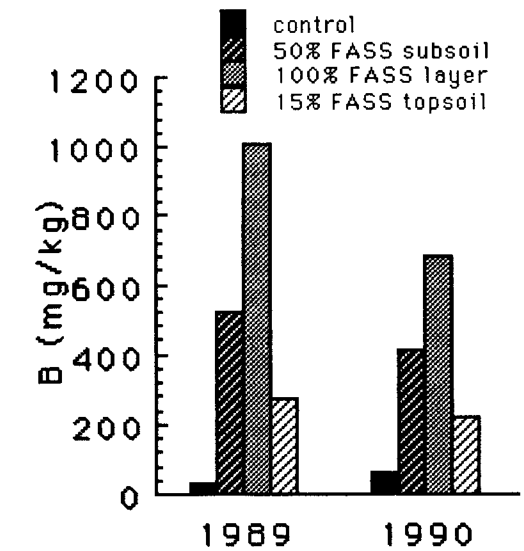
Treatment	1989	1990
	----- $kg\ ha^{-1}$ -----	
control	5965	6501
50% FASS in subsoil	3185	5927
100% FASS in layer	3005	5130
15% FASS in topsoil	4652	7548

Yield and appearance of alfalfa grown on FASS-treated soils in 1990 showed marked improvement over the 1989 season. Although B toxicity was evident, symptoms were subdued in comparison with those exhibited by the first year's crop. Plants exhibited whitening and necrosis of the leaf tips and margins, but the major part of the most leaves remained green and viable. Leaf drop due to B toxicity was limited. As in 1989, B toxicity symptoms were increasingly apparent during extended periods without precipitation and were most severe in treatments with subsurface layers containing FASS.

Alfalfa from the control lysimeter yielded 6501 kg/ha hay, slightly more than in 1989 (Table 6). Above-ground biomass production differences between treatments were considerably reduced in 1990. The 50% FASS/subsoil mixture and the 100% FASS subsoil treatments produced 91 and 79 percent as much biomass, respectively, as the control. Mean above-ground biomass production from the 15/85 FASS/topsoil treatment exceeded the control by 15 percent.

Elemental analysis of 1989 alfalfa leaves showed that levels of all nutrients except B were within their normal physiological ranges. Analysis of variance revealed significant ($p \leq 0.10$) differences in leaf B and Cl concentrations due to FASS addition. Mean B concentrations in leaves of alfalfa grown on FASS-treated soils were several hundred percent higher than the approximately 80 mg/kg toxicity threshold (Fig. 2). Leaf B concentrations and phytotoxicity symptoms increased during periods of low precipitation. Boron concentrations were highest in plants grown on lysimeters with subsurface layers containing FASS.

Figure 2. Effects of FASS on alfalfa leaf B content.

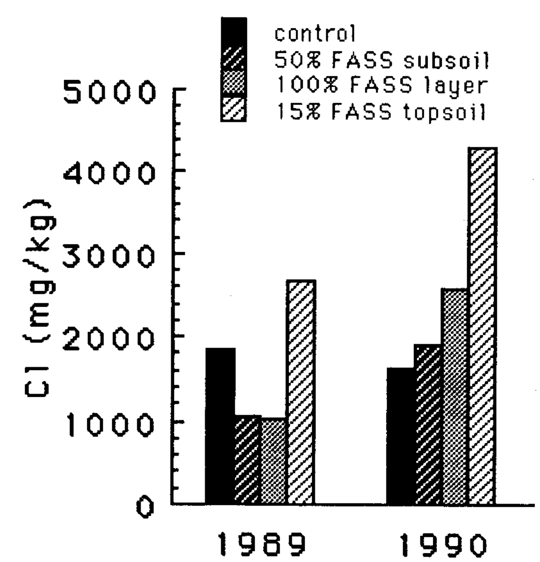


Mean alfalfa control leaf B was 61 mg/kg in 1990, as opposed to 33 mg/kg in 1989. Mean leaf B concentrations resulting from FASS addition followed the same pattern as in 1989, but levels were reduced by approximately 20 to 30 percent. Given the marked improvement in the appearance of the 1990 crop, lower physiological B levels were expected than actually occurred. It is possible that above-normal precipitation and more ideal soil water conditions allowed the plants to accumulate up to 1000 mg/kg B with comparatively less severe phytotoxicity effects. Boron enrichment ratios were highest in June and July harvests, but became progressively smaller as the growing season advanced. Leaf B levels for all treatments were approximately 2 to 3 times that of the control by the final 1990 harvest.

Chloride levels exhibited large monthly fluctuations in all treatments. Figure Fig. 3 shows that Cl uptake in the subsoil FASS treatments was reduced compared with the control. The differences were not significant ($p \leq 0.10$) due to large standard deviations in the control data. Boron toxicity, or perhaps some other interaction in the rhizosphere, appeared to inhibit Cl uptake. The significantly increased Cl uptake in the 15/85 FASS treatments is probably due to the very high soil Cl concentrations in the upper rooting volume. Mean leaf Cl for all treatments except the control were higher in 1990 than in 1989 (Wendell, 1992). As in 1989, the highest Cl accumulations occurred in alfalfa grown on the 15/85 FASS/topsoil mixture.

Boron toxicity effects in soybeans were most severe when 15% FASS was incorporated into the topsoil. Soybeans on two lysimeters so treated suffered 100% mortality within eight weeks of planting. Soybeans do

Figure 3. Effects of FASS on alfalfa leaf Cl content.



not root so deeply as alfalfa and the severity of phytotoxicity in this treatment is attributed to the majority of the rooting volume occurring in the upper 30 cm of the lysimeter and being in direct contact with the FASS/topsoil mixture.

Severe B toxicity symptoms occurred throughout the lifespans of plants grown on lysimeters containing FASS in subsurface layers. Mortality did not occur. Boron phytotoxicity appeared more severe in the treatment which contained 50% FASS incorporated into the subsoil. In addition to reduced stature, severe necrosis and leaf drop, remaining leaves often attained uncharacteristic oblong shapes, somewhat resembling willow leaves. Lateral branching and budding were increased over the control, but delayed maturity did not allow this phenomenon to translate into increased grain production.

Soybeans grown on the control lysimeter yielded 5583 kg grain per hectare in 1989 (Table 7). This is considered a very good yield. Treatments containing FASS in subsurface layers produced of just over 1000 kg/ha. Only one lysimeter of the three amended with 15% FASS in topsoil produced grain, at 1764 kg/ha. Wendell (1992) reviewed reported salt toxicity symptoms with fly ash addition to soils. Salt toxicity symptoms were not identified in this study, but may have been masked by B toxicity. However, osmotic effects on root function probably inhibited normal water and nutrient uptake, especially during periods of drought stress.

Above average precipitation improved soil water status and probably leached much soil B below soybean rooting volumes in 1990. Boron toxicity symptoms were less severe in soybeans grown on all FASS treated lysimeters. These plants exhibited characteristic B phytotoxicity symptoms including leaf necrosis, markedly reduced stature, increased lateral branches and greater numbers of pods per branch than the control. Leaf drop was limited and 100 percent survival occurred on all lysimeters. However, maturity was markedly delayed in comparison with the control. In the 1990 soybean treatments, FASS in subsoil layers rather than the 15/85 FASS/topsoil treatment exhibited the most severe B toxicity symptoms. This was in contrast to 1989, during which the 15/85 Fass/topsoil treatment

Table 7. Soybean grain yields from soils treated with fly ash scrubber sludge.

Treatment	1989	1990
	----- kg ha^{-1} -----	
control	5583	2760
50% FASS in subsoil	1049	553
100% FASS in layer	1019	428
15% FASS in topsoil	588	842

was most affected by B. Apparently much of the plant-available B had become immobilized or leached from the topsoil mixture by the 1990 growing season, or was removed in the 1989 crop.

Grain production in 1990 was reduced in comparison with 1989 (Table 7). Yields for all treatments were approximately 50% of their 1989 levels. All three lysimeters containing 15/85 FASS/topsoil mixtures yielded grain and averaged 842 kg/ha.

Elemental analysis of 1989 soybean leaves showed that levels of all nutrients except B and possibly Cl were within their normal physiological ranges. Analysis of variance did not show significant differences ($p \leq 0.10$) between leaf B content of plants grown on FASS-treated soils versus the control. However, the data show higher mean B concentrations (Fig 4). The differences are not statistically significant, partly because of large standard deviations in the data and partly because data were missing from lysimeters in which B phytotoxicity induced 100% soybean mortality.

Elemental analyses of soybean leaves in 1990 showed that levels of all nutrients except B and possibly Cl were within their normal physiological ranges.The 1990 soybean leaf elemental data (Fig. 4)) revealed reduced B enrichment compared with 1989. Boron levels in the control increased over the previous year. Analysis of variance showed significant differences ($p \leq 0.10$) between leaf B content of plants grown on FASS-treated soils versus the control. This contrasts with the 1989 data, in which large standard deviations masked treatment differences.

Soybean leaf Cl uptake patterns for the 1989 crop were similar to those for alfalfa. Chloride uptake was reduced in plants grown on lysimeters with subsoil containing FASS, but increased when 15% FASS was incorporated into topsoil (Fig. 5). Preferential uptake of B or phytotoxicity effects on roots may have inhibited Cl uptake in the subsoil treatments. The 'Williams 82' cultivar is sensitive to elevated soil Cl levels and at least mild Cl toxicity may have occurred in plants grown in the FASS/topsoil. Mortality associated with this treatment may have been due to a cumulative or possibly possible synergistic effect of salts and B phytotoxicity. Boron phytotoxicity was the cause of death.

Leaf Cl levels in 1990 exceeded those of 1989 in all treatments including the control. In contrast with 1989, all FASS treatments resulted in increased leaf Çl. Although the Williams 82 cultivar is susceptible to Cl toxicity (Yang, 1991), leaf scorch and other symptoms associated with Cl toxicity were not positively identified in the 1990 crop, and Cl levels were probably within the normal physiological range.

RECOMMENDATIONS

Boron in power plant wastes is the limiting factor in determining allowable amounts of combustion by-products applicable to agricultural soils. To prevent crop damage or loss due to B toxicity, amounts to be applied should be based on a worst-case scenario. With some crops, salinity may be a limiting factor if fresh FASS is applied. Analysis of AECI FASS reveals that, with rare exceptions, B will supersede salinity as the limiting factor in determining applications. Leaching and removal due to plant uptake should significantly diminish B toxicity after the first year. Data from the

Figure 4. Effects of FASS on soybean leaf B content.

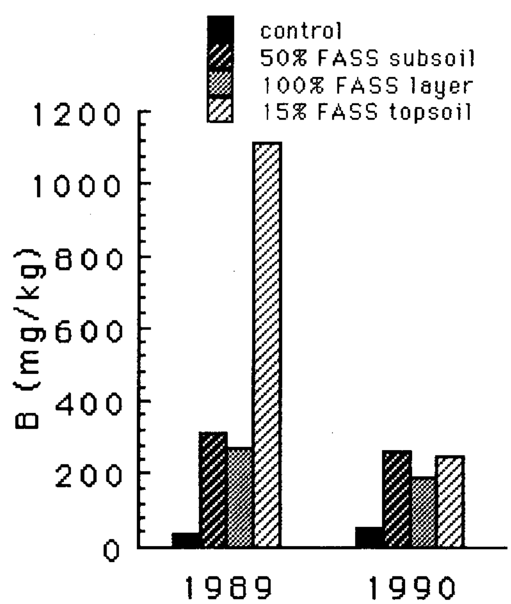
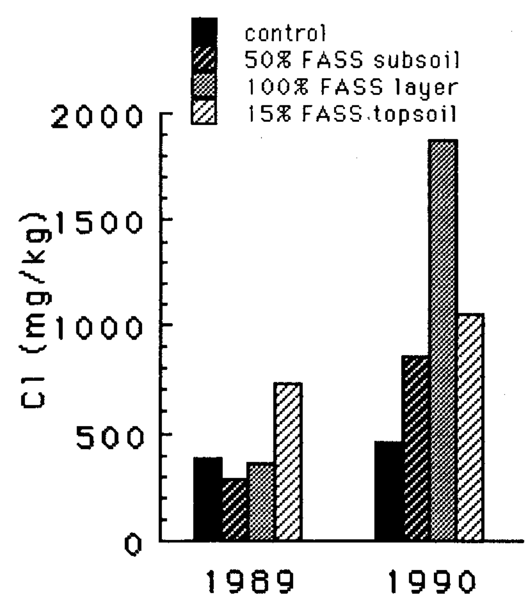


Figure 5. Effects of FASS on soybean leaf Cl content.



AECI power generating station wastes were used to develop application tables based on B contents. Recommendations are based on the following assumptions and conditions:

1. Boron is sequestered in the ash (<2 mm e.s.d) fraction of the by-product.
2. A physiologically safe target bulk soil/FASS mixture B content is 3.0 mg/kg. Soil/FASS mixture B levels will be the limiting factor in determining applications.
3. Salinity, Cl, heavy metals and other micronutrients will not be limiting.
4. Soil water conditions will affect B activity and uptake.
5. Legumes or other crops with high B tolerance should be grown in the first one to two years. Use of a "green manure" such as alfalfa, which can be incorporated into the soil may be the most effective management technique.
6. As a soil amendment, FASS should be incorporated to a depth of at least 30 cm. Soil and FASS will be mixed as thoroughly as possible.
7. A target soil surface layer bulk density should be approximately 1.3 Mg/m3. This would yield a soil weight of approximately 1800 tons/acre ft.
8. Higher FASS amounts can be incorporated by mixing into subsoil and overburden. This should result in decreased bulk densities and improved internal soil drainage. Incorporation of an organic mulch in addition to fly ash scrubber sludge is recommended.
9. Surface and groundwater quality will not be adversely affected.

The target B level of 3.0 mg/kg can be compared to average supplemental B fertilization amounts of 1.0 mg/kg (approximately 4.0 lb/acre ft). The 3.0 mg/kg level is safe for most crop plants. Fly ash scrubber sludge/soil mixtures will not be homogeneous, however. Soil aggregates or clods will be surrounded by coatings silt-sized FASS. Thus, B levels in the region where plant roots occur may be significantly higher than 3.0 mg/kg, while the interior soil aggregate B level will be unchanged. For an extra margin of safety, crops with a high physiological B demand, such as alfalfa should be used. Less B-tolerant crops could be planted after the first one or two years. Boron is an anion, so it is not well attenuated by soils. Boron in ash materials will be both readily taken up by plants and relatively quickly leached from the soil profile. Fly ash scrubber sludge could be applied periodically to surface soils as B levels are reduced, provided soils do not become too alkaline. Soil Se levels should be monitored and not allowed to increase to the point that Se accumulates in plants.

Coarse fragments (>2 mm e.s.d) are nearly chemically inert and have the effect of "diluting" concentrations of plant-available elements in power plant wastes. This becomes important if bottom ash or other materials containing coarse fragments are included. At a given ash (<2 mm e.s.d.) B level, the allowable application increases proportionally to the amount of coarse fragments present. Fresh AECI FASS contained less than 1.0% coarse fragments. Recommended applications were determined using the following equation:

$$\text{Tons/acre} = 1800 * (100/\text{fines }\%) * (3.0/\text{ B content})$$

The equation assumes an acre of soil at 1.3 g/kg bulk density weighs approximately 1800 tons/acre ft., and a target bulk soil/waste mixture B level of 3.0 mg/kg (3.0 ppm). For example, AECI FASS collected in March, 1991 contains 100% fines (no coarse fragments) and 70 mg/kg B;

$$1800*(100/100)*(3.0/70) = 77.1 \text{ tons/acre ft (4.3\% by weight)}$$

Boron in most AECI FASS exceeded 70 mg/kg, so the application determined in this example probably approximates the maximum amount which can be safely applied. Table 8 summarizes specific application recommendations for AECI FASS investigated. While the values reported valuable information concerning the properties of FASS from this specific power plant, they are not necessarily representative. Several sets of samples were collected over a three year period. More comprehensive sampling and analysis should be performed before implementing an actual application pro-

Table 8. Recommended application amounts for fly ash scrubber sludge samples.

sample date	mean B content (mg/kg)	recommended[1] application (tons/acre)
5/20/88	261.1	21
6/16/88	415.3	9
7/22/88	284.4	13
2/16/89	220.0	19
8/26/89	374.4	14
5/24/89	182.5	30
7/20/90	374.0	14
8/11/90	321.7	17
3/7/91	70.2	77
average	278.2	20

[1] Amounts are based on a soil/fly ash scrubber sludge mixture B content of 3.0 mg/kg and material mixed into the soil to a depth of 30 cm.

gram. Additionally, the data are for materials which have been subjected to various weathering regimes, which strongly influences chemical composition. Field investigations are needed to verify the recommendations.

The Thomas Hill plant burns about 15,000 tons of coal per day and generates 12% that amount, or 1800 tons/day FASS. If the FASS is composed of nearly 100% fines and contains 300 mg/kg B, an estimated 18 tons/acre foot or approximately 1.0% soil weight could be applied, achieving the target 3.0 mg/kg final B level. Approximately 100 acres/day, or 36,500 acres (57.0 square miles) per year could be treated if all FASS is to be incorporated into topsoil. Much less land would be required if FASS were incorporated into each overburden and soil layer during reclamation operations. Fly ash scrubber sludge additions could be substantially increased below the plant rooting volume.

The large area of land required makes complete reliance on land application as a means of managing FASS and other power plant by-products impractical. However, if implemented in conjunction with other programs, the majority of combustion by-products can be utilized, rather than disposed of in landfills.

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Fly Ash Scrubber Sludge Addition and Growth of Legumes and Grasses

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Abstract. Fly ash scrubber sludge (FASS) from Associated Electric Power Plant at Thomas Hill, MO was evaluated as a soil amendment.The addition of 2.5 or 5.0% FASS by weight to an acidic topsoil resulted in increased soil pH and salt level, and increased growth of Alfalfa (*Medicago sativa* L.). Birdsfoot Trefoil (*Lotus corniculatus* L.) and Tall Fescue (*Festuca arundinacea* L.).

Concentrations of Al, Ba, Ca, Cd, Cu, Fe, K, Mg, Ni, P, Si, Sr, Ti, and Zn in plant tissues were either unaffected or reduced due to addition of the FASS. The concentrations of B, Cl, Mo, Mn, and S were higher in tissues of plants grown on FASS treated soil than those grown on untreated soil. While As, Be, Bi, Co, Cr, Li, Pb, Sb, Se, Sn, TI, V, and W concentrations were all below the detection limits of the Inductively Coupled Plasma unit.

FASS improved soil water retention, served as a supplementary supply of Ca, S, Cl, B, Mo, and Mn, neutralized soil acidity, and increased plant growth. Boron content limited the amount of FASS that could be applied to soil. Boron concentrations in the range of 400 to 600 (mg B/kg) were observed in some tissues. Salt may also limit the amount of FASS applied. Addition of 5% FASS resulted in the salt levels predicted to be harmful to salt sensitive plants.

INTRODUCTION

The generation of electricity from coal produces approximately 100 million tons of waste annually in the forms of fly ash and scrubber sludge (Francis et al., 1983). The power plant operated by Associated Electric Cooperative, Inc.(AECI) near Thomas Hill, Missouri produce a single by-product termed "fly ash scrubber sludge" (FASS). AECI disposes of approximately 85,000 m^3 of FASS annually by burial in old surface mines. Although this disposal technique is safe and lawful, it is expensive. Preliminary investigations show that FASS added to soil at 25 and 50 %(w/w) resulted in favorable physical properties, but had undesirable chemical effects on plant growth. Our objectives are to characterize the effects of FASS added to soil at 2.5 and 5.0 %(w/w) on the growth and chemical composition of legumes and grasses.

EXPERIMENTAL METHODS

Samples of FASS and soil, a silty clay loam mixture of A horizons of Aquic Argiudolls, Aquic Hapludalfs, Typic Ochraqualfs, Typic Dystrochrepts, Typic Fluvaquents, and Typic Udipsamments removed by scrappers during mining, were collected from the Thomas Hill Plant of Associated Electric Cooperative, Inc. The samples were air-dried, ground, and sieved to pass a 2 mm screen. Potassium phosphate at 0.3 g P / kg soil and magnesium sulfate 0.5g/kg soil were added to all soils. Ammonium nitrate at 0.3g N /kg soil was added to the mixtures for non-legumes. Inoculates of *Rhizobium Meliloti* for alfalfa *Rhizobium Lotus* for birdsfoot trefoil were mixed with soil. 25g or 50g of FASS was mixed with a kilogram of soil. 650 g of soil-FASS mixture was placed in a 700 mL plastic pot and enough water added to reach the field capacity values shown in Figure 1. Four replicates for each plant specie were prepared and planted to alfalfa (*Medicago Sativa* L.), birdsfoot trefoil (*Lotus Corniculatus* L.), tall fescue (*Festuca Arundinacea* L.), and orchardgrass (*Dactylis Glomerata* L.). The pots were placed into four replicates to form a randomized block design.

The plants were grown in a room with 12 hours of light (29 to 30C) and 12 hours of dark (27 to 28C). Each day deionized water was added by weight to bring the water content to the original measured field capacity. After 6 weeks of growth the plants were cut at the soil surface, weighed, dried at 68C for 2 days, weighed, and ground to pass a 40 mesh screen. Samples were decomposed with HNO_3 and H_2O_2 and analyzed by inductively coupled plasma spectroscopy by the University of Missouri Trace Substances Laboratory (White and Douthit, 1985). A portion of the digest was analyzed for total

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chlorine by the Cl electrode (Gaines et al., 1984), and for total sulfate by the turbidimetric method (Blanchar et al., 1965).

Measurement of soil and FASS pH, organic matter content, neutralizable acidity, Bray 1 P, Ca , Mg, K, Na, Zn, Fe, Mn, and Cu were done by The Missouri Soil Testing Laboratory using methods described by Brown and Rodriquez (1983). Boron was extracted by hot water and determined by azomethine-H method (Bingham, 1982). Total C was determined by high temperature decomposition using a Leco CR-12. The electrical conductivity (EC) and concentrations of F, Cl, NO_3, P, and SO_4 in 1:1 soil to water extracts were measured using a conductivity meter and a Dionex anion exchange unit. Soil water retention was done by pressure-plate extraction (Klute A. 1986). Field capacity moisture was determined by the mud ball technique as described by Feng (1939) .

RESULTS AND DISCUSSION

FASS had a pH of 8.6 and contained considerable B, Ca, Cl, K, and S with low levels of C, Cu, Fe, Mn, N, P, and Zn (Table 1).

The pH, calcium carbonate equivalence, and total Al, Ca, and Fe of FASS shown in Table 1, when compared to samples taken over time by Wendell (1992), indicate this material is typical of FASS generated by AECI.

FASS used in this study is a high B ash when compared to those in the western United States, which average 24 mg kg^{-1} (Page et al., 1979) and those in the southeast, 22 to 55 mg kg^{-1} (Plank and Martens,1974).

Addition of FASS to soil increased pH, specific conductance, B, Ca, Cl, and SO_4 (Table 2). Soil salinity increases substantially with increased rate of application of FASS. The EC of 5% FASS mixtures reached about 4 dS m^{-1} which can be potentially harmful to some crops (Adriano et al., 1980). Boron, Cl, and SO_4 were present at much higher concentrations in FASS than in soil (Tables 1 and 2). It is evident that the increase of soil EC is associated with high Cl and S. The B content of control, 2.5%, and 5% FASS mixture are 1.64, 7.57, and 11.8 ppm (Table 2). The concentration of B in the 5% mixture is potentially harmful to some crops (Mengel and Kirkby, 1987a).

FASS has high water-holding capacity (Fig. 1). The moisture content at each pressure increased as the concentration of FASS in the soil increased. This is consistent with results of Chang et al. (1977) who found that fly ash added at 8% by weight significantly increased the soil water holding capacity. Since at -15 bar

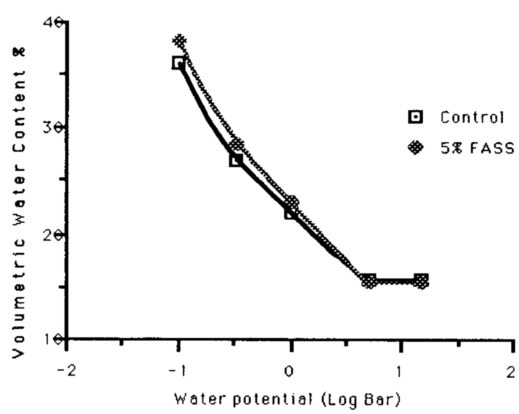
Table 1. Chemical properties of flyash scrubber sludge.

pH (0.01M CaCl2)		8.6
Calcium carbonate equivalence (%)		15
Total	Carbon (g kg^{-1})	7.5
	Aluminum (mg kg^{-1})	863
	Calcium " "	20040
	Iron " "	5933
Water soluble (1 to 1 extract)		mg kg-1
	Flouride	10.5
	Chloride	4270
	Nitrate	3.3
	Sulfate	2240
Hot water soluble Boron		261
Exchangeable (1M NH4Ac)		
	Calcium	8547
	Magnesium	227
	Potassium	354
	Sodium	274
DTPA Extractable		
	Copper	1.85
	Iron	64.5
	Manganese	6.0
	Zinc	3.6

Table 2. Chemical properties of flyash scrubber sludge-soil mixtures.

	SOIL	FASS 2.5%	FASS 5.0%
pHs (0.01M CaCl2)	5.1	5.7	6.2
Organic Matter %	2.1	2.0	2.0
Conductance dS m-1	1.65	2.83	3.36
Acidity cM kg-1	5.7	3.7	2.0
Bray No. 1 P mg P/kg	194	164	151
EXCHANGEABLE (1M NH4Ac)		- mg kg^{-1} -	
Calcium	2379	5670	8715
Magnesium	540	480	594
Potassium	348	340	345
Sodium	154	157	175
Chloride	——	25	39
Soluble Sulfate	331	641	689
Hot Water Soluble Boron	1.6	7.6	11.8

Figure 1. Water retention of soil and 5% FASS.



pressure the volumetric water contents of soil with and without 5% flyash are the same, increased field capacity moisture due to fly ash addition also increased available moisture (Fig. 2). Field capacity moisture was determined as the limit of capillary conductivity using the mudball technique and corresponds to a matrix pressure of about -0.7 bar.

Addition of FASS significantly increased the growth of alfalfa, birdsfoot trefoil, and fescue, and with significant effect on orchardgrass (Fig. 3). Yield differences between treatments of 2.5 and 5% FASS were not statistically significant for any plant species.

Concentrations of 2.5 and 5% FASS were chosen because in a preliminary study concentrations of 25 and 50% reduced germination and growth (unpublished data). It was concluded that both high Cl and B were factors reducing growth when FASS was applied at 25 and 50%.

Figure 2. Field capacity moisture content of soil, soil flyash mixtures, and flyash.

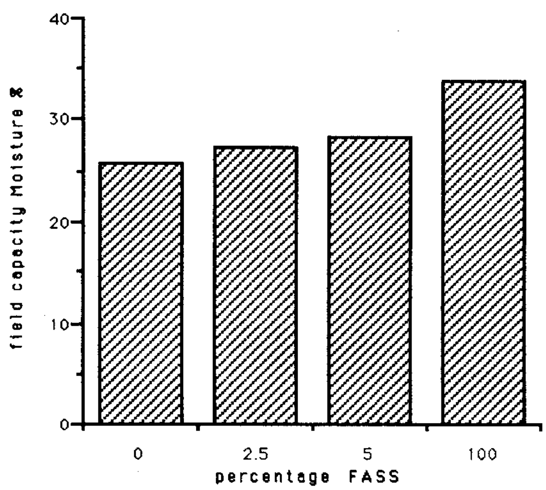
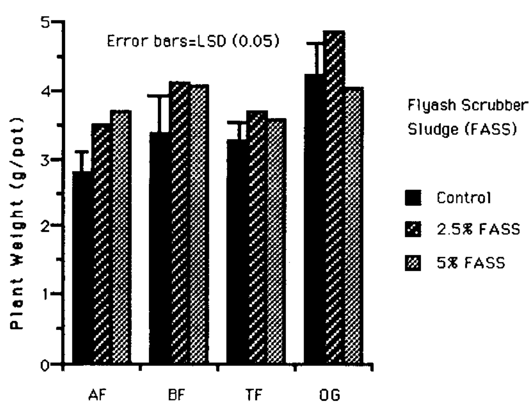


Figure 3. Effect of FASS on Growth of alfalfa (AF), birdsfoot trefoil (BF), tall fescue (TF), and orchardgrass (OG).



The concentrations of elements in the plant tissues were determined by ICP analysis of hydrogen peroxide and nitric acid digests of the tissues. Those elements whose concentrations were below the detection limit of the instrument are given along with the detection limits in Table 3.

Mean concentrations of elements whose concentrations in plants were not significantly changed by FASS addition are shown in Table 4.

FASS addition had no effect or slightly decreased the concentrations of Ca, Cd, Cu, K, Mg, Na, Ni, P, Ti, and Zn in alfalfa and birdsfoot trefoil stems and leaves and in the whole plant tissue of fescue and orchardgrass (Table 4). Calcium, Mg, and Cd concentrations of leaves of both alfalfa and birdsfoot trefoil were higher than in stems (Table 4). Phosphorus concentrations in

Table 3. Summary of elements that were below the detection limit of the ICP unit.

ELEMENT	Detection Limit
	mg kg^{-1}
Antimony	4.0
Arsenic	4.0
Beryllium	0.1
Bismuth	4.0
Chromium	1.0
Cobalt	1.0
Lead	4.0
Lithium	0.2
Selenium	5.0
Silver	1.0
Thallium	4.0
Tin	4.0
Tungsten	1.0
Vanadium	0.3

Table 4. Mean elemental Concentration in alfalfa (AF), birdsfoot trefoil (BF), tall fescue (TF), and orchardgrass (OG) that were not changed due to FASS addition.

Element	AF		BF		TF	OG
	stem	leaf	stem	leaf	entire	plant
	%					
Ca	0.93	2.23	0.58	1.64	0.60	0.48
K	3.32	3.09	3.70	3.40	4.70	5.55
Mg	0.18	0.39	0.17	0.41	0.38	0.27
P	0.55	0.37	0.58	0.28	0.48	0.52
	mg/kg					
Cd	0.7	1.9	1.1	1.4	1.0	0.5
Cu	13	15	11	11	13	20
Na	174	150	58	92	388	270
Ni	3.6	3.6	4.3	5.8	3.2	3.1
Ti	6.8	5.3	3.8	3.6	3.0	4.4
Zn	19	30	44	44	40	39

stems of alfalfa and birdsfoot trefoil were higher than in leaves. These elemental distributions between stems and leaves are consistent with those reported in the text by Mengel and Kirkby (1987b).

FASS addition significantly decreased Al (Fig. 4). The decrease in Al concentration is attributed to increased pH associated with FASS addition (Table 2). Decrease Al concentration in legumes may contribute to better symbiotic nitrogen assimulation (Tisdale et al., 1985b).

Ba (Fig. 5) and Sr (Fig. 6) concentration were also significantly reduced due to FASS addition. Decreased concentrations of Ba in plant tissue due to FASS addition may in part be due to decreased Ba solubility in soil associated with increased sulfate added with FASS (Table 1 and 2).

In every case, increasing the amount of FASS added to the soil decreased the concentration of Sr in plant tissue (Fig. 6). Decreased concentrations of Sr in plants may be due to Ca added with FASS and the associated dilution by Ca during the uptake process (Mengle and Kirby, 1987b).

Figure 4. Al concentration in AF, BF, TF, and OG.

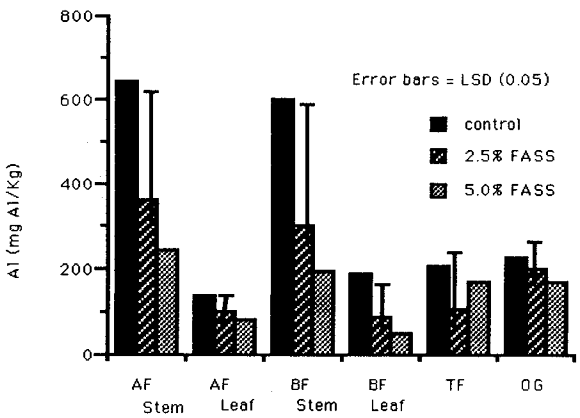
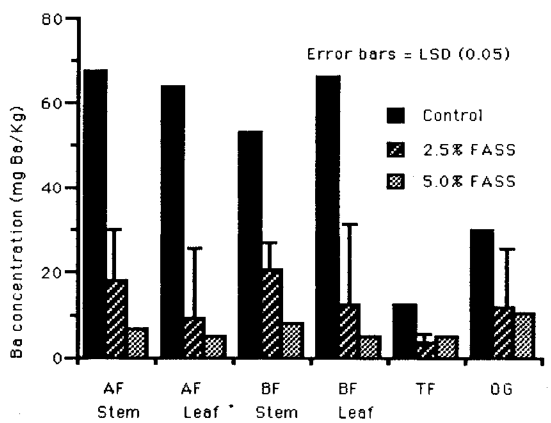


Figure 5. Ba concentration in AF, BF, TF, and OG.



Iron concentrations in alfalfa and birdsfoot trefoil were reduced due to FASS addition (Fig. 7). Decreases in Fe concentration in alfalfa and birdsfoot trefoil would be expected as pH increased due to FASS addition. However, the same decrease was not observed in Fe concentration for fescue and orchardgrass (Fig. 7). The reduction in Fe concentration in alfalfa and birdsfoot trefoil stems was greater than in leaves.

Concentrations of Mn, Mo, B, Cl and S were all increased by FASS addition. Concentrations of Mn are shown in Fig. 8. Increased Mn concentration in alfalfa and birdsfoot trefoil leaves and in fescue and orchardgrass grass with FASS addition was not expected. However the concentrations are in a range considered normal (Ohki, 1981).

Molybdenum availability is predicted to increase as pH increases (Stout et al., 1951). FASS addition increased pH and Mo as shown in Fig. 9.

Figure 6. Sr concentration in AF, BF, TF, and OG.

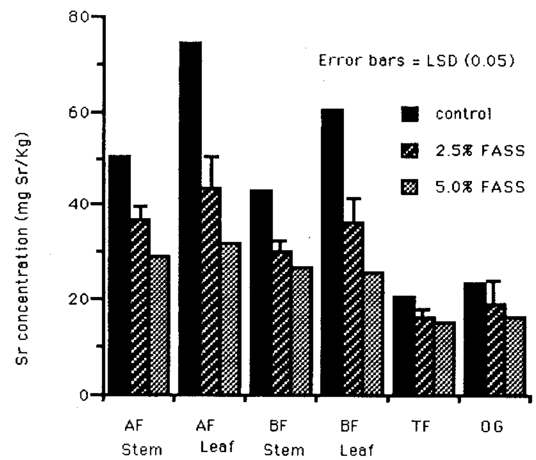
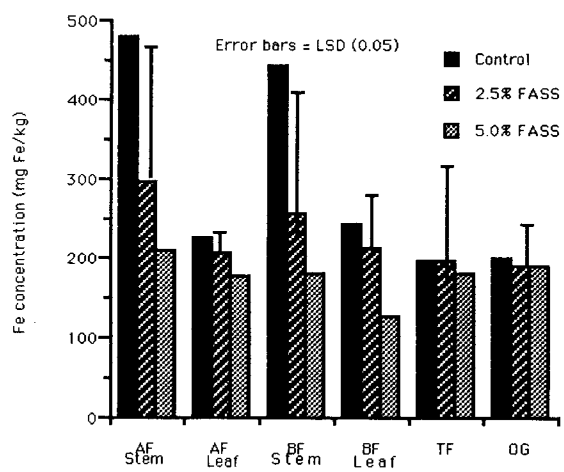


Figure 7. Fe concentration in AF, BF, TF, and OG.



Boron appeared to be one of the factors limiting the amount of FASS that could be added to soil. Data presented in Fig. 10 show the dramatic increases in B concentration in plant tissues due to FASS addition. Boron concentrations in the leaves of alfalfa and birdsfoot trefoil and in fescue and orchardgrass are high enough to be of concern, particularly at the 5% FASS concentration (Mengle and Kirkby, 1987a).

Figure 8. Mn concentration in AF, BF, TF, and OG.

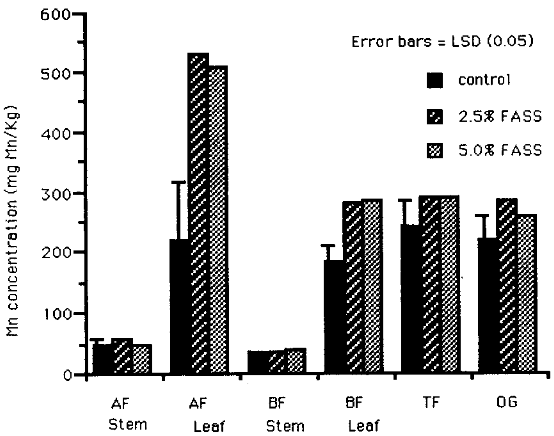


Figure 9. Mo concentration in AF, BF, TF, and OG.

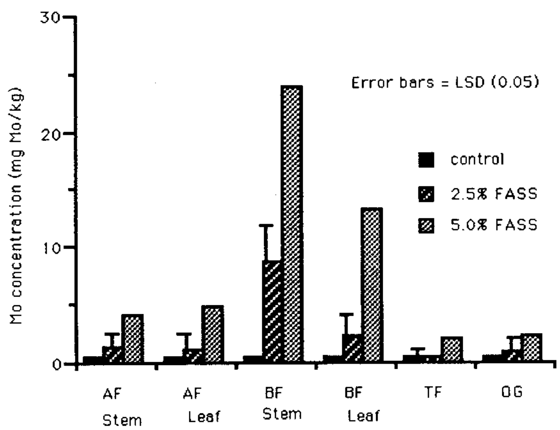
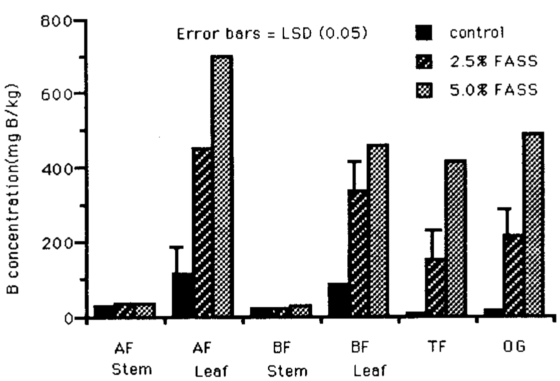


Figure 10. B concentration in AF, BF, TF, and OG.



Chloride concentrations were also increased due to FASS addition (Fig. 11). Chloride concentrations (Table 2) in the range of 0 to 40 mg kg^{-1} are not normally thought to reduce growth (Tisdale et al., 1985a). The data suggest boron rather than chloride may limit the amounts of FASS that can be applied to soil.

Increased S added with FASS shown in Fig. 12 may be beneficial to growth. Levels of S less than 1% have not been reported to be detrimental to plant growth. The S added with FASS should be considered an asset. Plant composition changes observed in this study are consistent with those that would be predicted due to additions with FASS or with changes in soil pH.

SUMMARY

Preliminary studies where FASS was added to soil in amounts of 25 and 50% (w/w) indicated severe damage to plants. Salt damage was severe and most plants died. The soil was leached to remove excess salts and in this case the plants grown at 50% FASS died due to B toxicity. At 25% FASS B toxicity reduced growth to less than a quarter of that on the control soil. It appeared that salt and B were going to limit the amount of FASS that could be added to soil.

Figure 11. Cl concentration in AF, BF, TF, and OG.

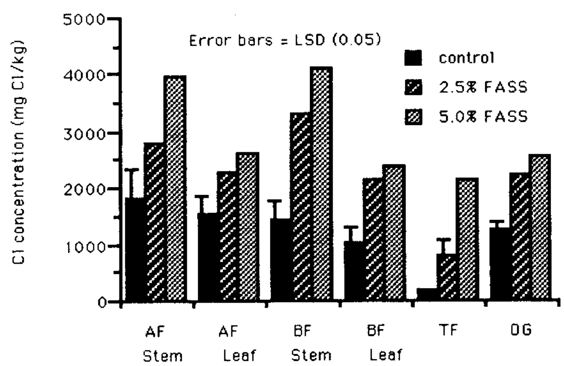
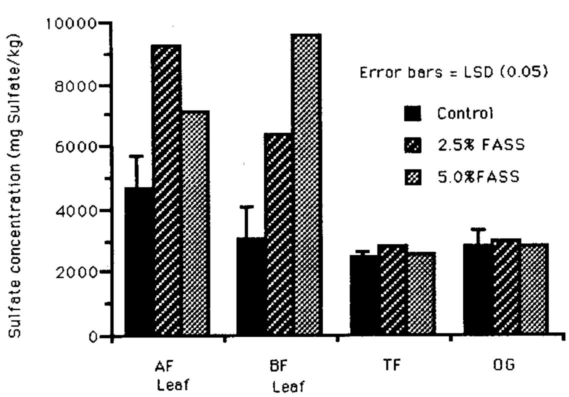


Figure 12. Sulfate concentration in AF, BF, TF, and OG.



Alfalfa, birdsfoot trefoil, tall fescue, and orchardgrass were grown in soils to which 0, 2.5 and 5% FASS was added. Alfalfa, birdsfoot trefoil, and fescue growth was increased due to the addition of 2.5% FASS, while orchardgrass was not significantly changed. Addition of 5% FASS resulted in salt levels in the soil predicted to be harmful to salt sensitive plants.

FASS addition either decreased or had no significant effect on the concentrations of the 35 elements in the various plant tissues. In the case of the heavy metals this was attributed to increased pH due FASS addition. B, Mn, Mo, Cl and S concentrations were increased due to FASS addition. Increases of B, Cl and S are probably due to the large amount added with FASS. Higher Mo may be due to increased availability with increased pH. No explanation is offered for increased Mn content in the plant with increased FASS.

FASS has soil amendment properties which suggest that it may be beneficial to plant growth under some conditions. Improved water retention, pH, Ca, S and at low concentrations B are beneficial aspects. At high concentrations of FASS salt and B become limiting factors and may be harmful to plants.

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Effect of Nitrogen, Phosphorous and Potassium on Yield and Leaf Composition of Corn Grown on Scraper Placed Mine Soil

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Abstract. Response of corn grown on scraper placed soil media to annual applications of selected rates and combinations of N, P, and K was measured at the Denmark mine site in southern Illinois. Rates of N, P, and K ranged from 0 - 200 lbs/a, 0 - 80 lbs/a and 0 - 120 lbs/a, respectively. Treatment combinations were arranged to conform to a modified central composite design where treatments were randomized in three replications of a randomized complete block design. Ten to 12 random leaf samples were obtained from each plot (30 ft x 40 ft) each year at early silking (approximately R1) and yield estimates were obtained at maturity.

As expected the effects of N, P and K upon yield and chemical composition varied from year to year. In 1988, there was a significant N linear x P linear interaction that affected corn yield. Fertility variables did not significantly affect corn yields in 1989 or 1990. Nitrogen fertilizer was the most frequent element affecting leaf composition, but the effect was not consistent each year.

In general, corn yields in this study have been lower than those frequently observed on natural soils, suggesting that other factors such as moisture stress may have limited crop yield and, perhaps, response to fertilizer variables. Although some of the variation in chemical composition of the corn leaf in any particular year could be attributed to one or more fertility variables, the concentration of plant nutrients in the leaf was generally sufficient for higher yields than those observed. Corn yield and/or leaf composition was affected by one or more fertilizer variables each year of this study and fertilizer applications should be considered as a necessary part of the management of reclaimed soils for crop production. However, other management or climatic factors may also influence corn yields and affect response to fertility variables.

INTRODUCTION

Response of corn (Zea maize) to N, P and K fertilizer has been measured in innumerable experiments in the twentieth century. However, relatively few experiments have been conducted evaluating response on reclaimed minesoils. Dancer (7) found that more extractable P was required in minespoil to support maximum corn production than was required for topsoil. In some areas P is often deficient for revegetation, but K is usually sufficient (8). Others have found that P rates may need upward revision for wheat grown on minespoil but no revisions were needed for corn silage production (3). Sutton and Dick (16) indicated that establishment of vegetation on mined lands was often hindered by low availability of plant nutrients and soil moisture. In many cases the limiting fertility factor was soil acidity. In a study of corn yield response to a factorial arrangement of P and K rates, Barnhisel and Semalulu (2) observed a linear corn yield response to K at one location and a quadratic K response and a linear P x linear K response at another location. Corn leaf nutrient response to fertility rates also varied between locations. Various factors including different soil construction methods may have contributed to the differential responses.

It has been established that different soil construction methods studied in Illinois affect soil physical properties and subsequent crop yield when compared to natural soils (9,10). McSweeney et al., (9) found that minesoils built with scrapers produced less corn and soybeans than soils constructed by other methods. The scraper system produced a more compact subsoil which limited root development and plant-available moisture. Stucky and Lindsay (15) studied the effect of compaction upon soybean growth and yield. They reported that in all instances plants grown on soil compacted to a bulk density of 1.4 g/cm^3 outyielded those grown on soil compacted to 1.6 g/cm^3. Barnes et al., (1) reported the development of compact layers in reconstructed soils due to repetitive trips by scrapers. They indicated that the adverse effect varied due to soil media texture, moisture content and machinery traffic. Wolkowski (18) indicated that the effects of compaction might result in a decrease in N availability and reduction in K uptake due to lower root respiration. He also indicated that fertilization may compensate partially for yield limitation. McFee et al., (11) reported that N, P, and K were less effective than sludge, but usually produced increased plant growth.

Soil media characteristics other than plant nutrients may have received more emphasis due to the severe effects of compaction on crop growth and yield. Some research has been conducted evaluating soil fertility and soil test methodology as it relates to reclaimed minesoil (4,5,7). It has been suggested that plant nutrient research on reclaimed land should be at two or three rates and they should represent a broad range of application so that results can be plotted as nutrient response curves (8).

The objective of this research was to evaluate corn yield and leaf composition response to various rates and combinations of N, P, and K on scraper placed soil media.

MATERIALS AND METHODS

The experimental site was located at the Denmark mine in Perry county in southern Illinois. The mine soil at this site consists of 8 inches of scraper-placed topsoil over 40 inches of scraper placed rooting media. The area was deep tilled to a depth of approximately 32 inches in 1985 using the Kaeble-Gmeinder TLG-12. Experimental plots were 20 ft x 30 ft and planted to eight rows of corn. In 1988 and 1989 the hybrid planted was LH119xLH51 and in 1990 an early maturing hybrid (FS6566) was selected due to late planting.

It was assumed in this study that a quadratic polynomial was sufficient to characterize corn yield and other parameters of interest. Thus, fertilizer rates and combinations were selected to conform to a modified central composite design (6). Twenty - three treatment combinations of N, P and K were randomized in three replications of a randomized complete block design. Fertilizer rates and combinations were broadcast annually and disced prior to planting. After the first year (1988) fertilizer effects consist of response to the annual application plus residual effects. At approximately the early silking stage of development (R1) 10 - 15 randomly selected leaf samples were taken from each plot, dried, and sent to Brookside Farms Laboratories for determination of leaf levels of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn and Zn. Fertilizer sources of N, P, and K were ammonium nitrate, superphosphate and muriate of potash.

Soil samples were obtained from each plot each year and analyzed for pH, P and K by Brookside Farms Laboratories, which use the Mehlich 3 extractant and values were adjusted to Bray P1 and ammonium acetate extractable K. At the initiation of the experiment, soil pH, P and K averaged 6.5, 28 lb/a, and 136 lb/a, respectively. Soil pH ranged from 4.8 to 7.6, soil P ranged from 19 to 42 lb/a and soil K ranged from 112 to 256 lb/a. Agricultural limestone was applied to individual plots to adjust soil pH prior to planting in 1988.

RESULTS AND DISCUSSION

1988

Corn was seeded on May 5 at a rate of 23,200 seeds per acre under dry soil conditions. Emergence and stand establishment was characterized as good to very good. Precipitation in May was well below normal, and droughty conditions continued through the month of June. Severe early season stress symptoms were observed on all plots. Total rainfall for the month of June was only 1.7 inches coupled with above normal temperatures. The average maximum temperature for the entire months of June, July, and August exceeded 90° F each day. Late July rainfall aided pollination, but weather stress undoubtebly affected yield response.

Treatment means and results of the analysis of variance for 1988 are presented in Tables 1 and 2. Corn yield was significantly effected by both N and P fertilizer and the response is illustrated in Fig. 1. Yield response to N was greater at lower levels of P, and response leveled off at about 150 lb/a. Percent N in the corn leaf increased linearly within the rates of N used in this experiment (Fig. 2). Leaf percent K increased in the as rate of K increased and the effect was enhanced at higher rates of N (Fig. 3). Leaf Mg was also affected by N and K rates (Fig. 4) and the K effect was increasingly negative as rate of N increased (Fig. 4). Walker and

Figure 1. Corn yield response to N at two P rates (1988).

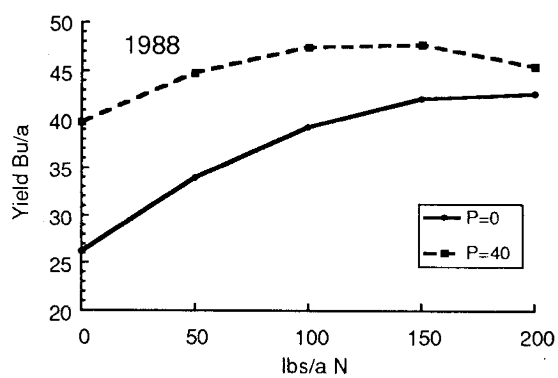


Table 1. Treatments, average corn yield and leaf composition from the Denmark Fertility Experiment, 1988.

Fertilizer Treatment N P K	Trt#	Reps	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
			Percent						Parts per Million					Bu/a
050-20-030[1/]	1	3	2.37	0.24	1.69	0.54	0.42	0.25	22.2	156.9	178.6	9.2	55.6	50.4
050-20-090	2	3	2.44	0.26	1.78	0.55	0.40	0.25	28.3	149.2	127.6	15.0	34.8	27.9
050-60-030	3	3	2.28	0.24	1.75	0.57	0.40	0.27	24.8	149.2	168.7	10.9	30.6	53.5
050-60-090	4	3	2.51	0.28	1.67	0.62	0.46	0.34	27.7	144.5	150.8	14.2	41.2	52.6
150-20-030	5	3	2.64	0.26	1.43	0.58	0.50	0.34	25.7	142.2	111.2	13.7	42.5	46.3
150-20-090	6	3	2.70	0.25	1.53	0.60	0.52	0.36	25.8	170.0	165.5	13.9	44.0	39.6
150-60-030	7	3	2.52	0.25	1.46	0.57	0.46	0.31	24.7	160.8	153.2	10.8	41.8	46.6
150-60-090	8	3	2.70	0.25	1.86	0.50	0.38	0.30	25.4	158.1	191.7	11.3	45.9	49.1
100-40-060	9	3	2.80	0.29	1.61	0.61	0.49	0.34	30.2	153.3	131.9	13.2	40.4	40.3
000-40-060	10	3	2.15	0.24	1.53	0.61	0.40	0.38	28.1	137.9	123.3	14.7	33.3	35.1
200-40-060	11	3	2.83	0.29	1.68	0.56	0.48	0.34	27.2	167.8	152.5	12.4	45.8	51.3
100-00-060	12	3	2.43	0.24	1.99	0.42	0.34	0.27	24.0	145.4	146.4	11.3	47.9	33.5
100-80-060	13	3	2.60	0.26	1.60	0.59	0.44	0.28	27.5	162.9	126.7	15.2	37.2	59.4
100-40-000	14	3	2.64	0.26	1.59	0.54	0.46	0.37	26.5	168.7	204.3	17.0	47.9	56.1
100-40-120	15	3	2.45	0.24	1.82	0.50	0.37	0.25	29.0	145.8	162.5	11.0	40.3	46.2
000-00-000	16	3	2.02	0.23	1.58	0.47	0.32	0.35	27.9	164.0	125.2	14.5	34.9	27.3
000-00-120	17	3	2.03	0.22	1.76	0.53	0.32	0.27	27.4	130.6	131.5	19.6	25.4	30.5
000-80-000	18	3	2.05	0.23	1.63	0.51	0.34	0.30	26.3	133.3	169.8	10.7	29.3	47.4
000-80-120	19	3	2.14	0.26	1.72	0.56	0.35	0.27	28.6	126.5	113.7	9.3	27.4	49.3
200-00-000	20	3	2.58	0.26	1.44	0.62	0.60	0.44	27.6	160.5	176.4	14.4	59.9	41.2
200-00-120	21	3	2.59	0.26	1.89	0.47	0.40	0.24	24.4	164.5	136.1	12.9	47.4	47.3
200-80-000	22	3	2.77	0.27	1.36	0.63	0.55	0.39	27.0	161.2	120.8	14.6	40.9	33.7
200-80-120	23	3	2.97	0.27	1.80	0.49	0.41	0.31	28.9	194.0	185.3	17.4	48.6	48.0

[1/] Fertilizer treatments are lbs/acre of elemental nitrogen, phosphorous, and potassium, respectively.

Table 2. Error mean squares and F ratios measuring the effect of fertilizer rates upon corn yield and leaf composition on the Denmark Fertility Experiment, 1988.

Sources of Variation	DF	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
		F Ratio											
Total	68												
Blocks	2	13.21*	7.10**	12.97**	10.36**	23.92**	15.69**	0.35	4.28*	7.35**	0.17	6.17**	5.65**
Treatments	22												
N Linear	1	7.17*	0.45	0.54	0.01	1.72	0.94	0.32	0.01	0.83	0.66	4.05*	3.03^{+}
P Linear	1	0.57	2.73	2.12	2.33	2.11	0.72	0.14	0.54	1.59	0.84	0.34	2.38
K Linear	1	0.13	0.93	0.15	1.37	0.37	0.17	0.17	1.85	5.22*	0.05	1.33	0.62
N Quadratic	1	1.67	0.54	2.58	0.73	0.26	2.45	0.22	0.06	1.47	0.12	1.16	1.47
P Quadratic	1	0.91	1.71	2.10	1.38	1.65	1.51	0.39	0.01	1.70	0.01	0.38	0.25
K Quadratic	1	0.26	0.79	0.01	0.60	0.29	0.01	0.30	0.12	3.32*	0.43	0.07	0.27
N*P Linear	1	1.19	1.01	0.11	0.10	0.56	0.15	0.29	3.28^{+}	0.01	7.21*	0.21	4.34*
N*K Linear	1	0.08	1.32	5.34*	4.70*	5.33*	1.17	0.22	5.09*	2.99^{+}	0.31	0.56	0.49
P*K Linear	1	0.78	0.81	0.01	0.09	0.01	0.72	0.69	1.80	0.15	0.19	3.63^{+}	0.20
Residual MS	13	0.3288	0.0013	0.096	0.0057	0.0174	0.0079	12.121	727.413	998.699	21.53	231.69	229.17
Error MS	44	0.0498	0.0005	0.321	0.0114	0.0072	0.0074	23.192	475.508	1803.188	15.20	89.15	169.24

**, Statistically significant at the 0.01 level.
*, Statistically significant at the 0.05 level.
$^{+}$, Statistically significant at the 0.10 level.

Figure 2. Response of leaf N to rate of N (1988).

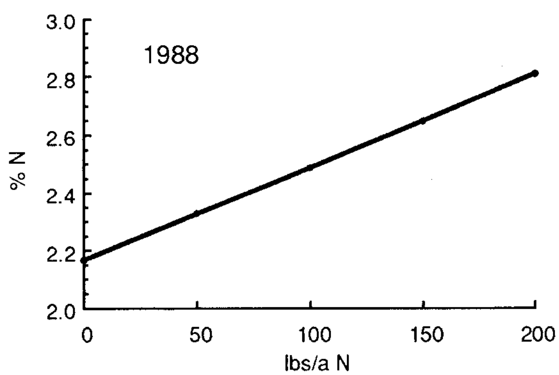
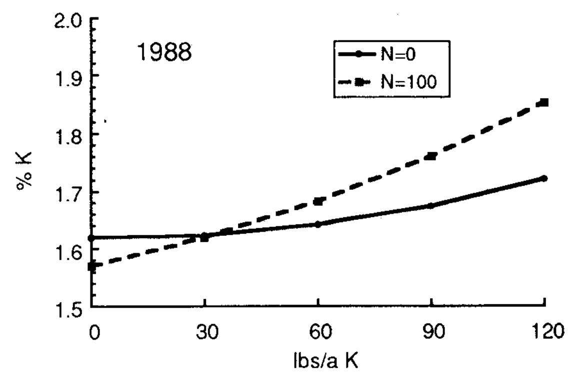


Figure 3. Response of leaf K to rate of K at two N rates (1988).



Peck (17) also reported a negative K effect upon corn leaf Mg in southern Illinois. Leaf Cu was affected by both N and P rates (Fig. 5).

1989

Corn was planted on May 6 under very favorable soil moisture conditions. Subsequent rainfall aided emergence and stand establishment. Below normal precipitation and above normal temperatures characterized the late June and early July growing period. Rain in mid-July aided pollination, but very high temperatures and below normal rainfall in the late-July to mid-August growing season resulted in visible stress symptoms appearing on all plots.

Treatment means and analysis of variance results for 1989 are presented in Tables 3 and 4. Fertility treatments did not significantly affect corn yield in 1989, but did significantly affect leaf composition. Leaf N increased with increasing rates of N (Fig. 6) and values observed were somewhat higher than those observed in 1988. Leaf P increased with increasing levels of P, but the effect was greater at low N rates (Fig. 7). Both N and P had a more significant effect upon leaf K in 1989 than did fertilizer K (Table 4). The effects of N and P are illustrated in Fig. 8 which shows that maximum leaf K occured at about 100 lb/a of N. Leaf Cu was affected by P rate, but levels observed were adequate. Effects of N and P are illustrated in Fig. 9. Leaf Zn increased as N rate increased and there was a small negative effect of P upon leaf Zn (Fig. 10).

Figure 4. Response of leaf Mg to rate of K at two N rates (1988).

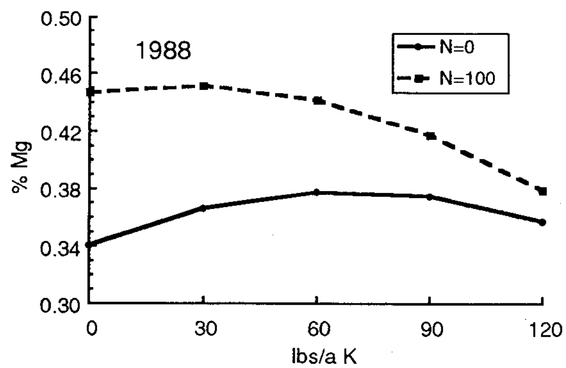


Figure 5. Response of leaf Cu to rate of P at two N rates (1988).

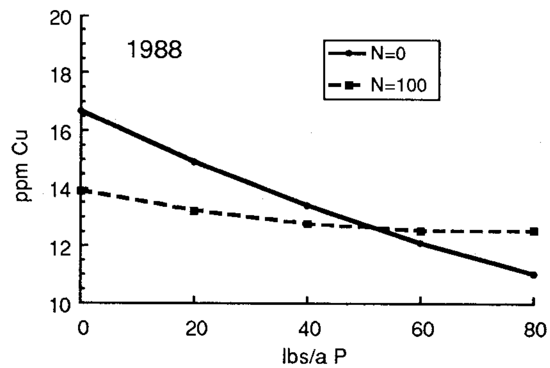


Table 3. Treatments, average corn yield and leaf composition from the Denmark fertility experiment, 1989.

Fertilizer Treatment	Trt#	Reps	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
N P K			Percent						Parts per Million					Bu/a
050-20-030[1/]	1	3	2.38	0.29	2.09	0.65	0.35	0.27	6.5	124.1	79.5	11.8	26.6	54.3
050-20-090	2	3	2.64	0.28	2.14	0.66	0.38	0.27	7.7	127.1	94.6	11.7	29.2	48.4
050-60-030	3	3	2.54	0.29	1.89	0.55	0.36	0.32	5.1	106.8	99.4	10.0	24.5	44.6
050-60-090	4	3	2.86	0.33	2.39	0.71	0.32	0.29	6.2	132.4	87.4	13.0	21.6	62.7
150-20-030	5	3	2.96	0.32	1.91	0.82	0.47	0.43	7.9	135.1	107.6	14.6	30.3	59.4
150-20-090	6	3	3.38	0.33	2.01	0.67	0.51	0.35	7.2	133.6	144.1	16.1	42.6	60.1
150-60-030	7	3	3.02	0.31	1.99	0.81	0.52	0.39	6.8	157.2	134.1	14.1	30.9	68.1
150-60-090	8	3	3.11	0.33	2.33	0.69	0.41	0.36	7.1	138.6	174.0	15.1	37.9	59.7
100-40-060	9	3	2.94	0.31	2.15	0.75	0.43	0.42	7.0	137.7	108.8	15.1	25.6	55.2
000-40-060	10	3	2.50	0.31	1.76	0.61	0.35	0.27	6.4	106.8	85.3	11.1	23.9	38.1
200-40-060	11	3	3.26	0.33	2.02	0.75	0.41	0.39	7.2	146.7	129.4	16.8	31.2	67.3
100-00-060	12	3	3.22	0.33	2.42	0.61	0.40	0.32	6.1	142.7	106.7	15.5	38.6	53.0
100-80-060	13	3	2.86	0.32	2.33	0.77	0.45	0.39	6.4	169.8	123.0	15.9	22.2	50.6
100-40-000	14	3	3.13	0.31	1.84	0.71	0.53	0.37	6.7	127.2	153.3	13.1	34.6	57.3
100-40-120	15	3	2.62	0.29	2.19	0.63	0.32	0.33	6.7	125.0	94.5	11.8	24.8	57.8
000-00-000	16	3	2.37	0.28	1.96	0.54	0.40	0.34	6.9	102.1	94.1	11.4	27.3	38.2
000-00-120	17	3	2.16	0.26	1.92	0.52	0.26	0.23	6.2	94.9	69.2	10.0	22.8	45.7
000-80-000	18	3	2.12	0.31	1.59	0.64	0.37	0.29	5.1	99.7	58.0	10.8	18.2	48.9
000-80-120	19	3	2.44	0.36	1.86	0.61	0.32	0.32	4.6	114.2	66.1	12.7	19.6	41.0
200-00-000	20	3	3.32	0.31	1.79	0.72	0.51	0.40	7.1	137.4	174.4	17.1	52.5	48.8
200-00-120	21	3	3.67	0.35	2.19	0.70	0.48	0.28	7.1	138.0	134.6	19.1	48.9	57.0
200-80-000	22	3	3.27	0.32	1.50	0.95	0.71	0.38	8.9	154.2	159.5	15.1	27.3	70.2
200-80-120	23	3	2.97	0.30	2.10	0.62	0.31	0.31	6.7	142.3	148.0	14.8	29.6	52.1

[1/] Fertilizer treatments are lbs/acre of elemental nitrogen, phosphorous, and potassium, respectively.

1990

Excessive spring rainfall resulted in delayed planting in 1990. Soils remained in a saturated condition until late June. A short season hybrid (FS6566) was substituted for the hybrid used in the previous years. The change in hybrids and late planting undoubtedly affected 1990 results. May precipitation was twice the average, June rainfall was near normal, but drier conditions prevailed in July and August with only 75% of normal rainfall.

Table 4. Error mean squares and F ratios measuring the effect of fertilizer rates upon corn yield and leaf composition on the Denmark Fertility Experiment, 1989.

Sources of Variation	DF	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
		F Ratio											
Total	68												
Blocks	2	1.97	0.12	2.62^{+}	5.04*	0.02	11.96**	2.29	1.54	1.68	4.10*	4.78*	17.88**
Treatments	22												
N Linear	1	6.33*	1.79	6.75*	2.57	4.02*	2.71	0.01	10.95**	6.79*	4.50*	3.75^{+}	2.27
P Linear	1	0.05	0.14	5.93*	0.78	0.02	0.01	0.01	3.05^{+}	0.21	2.86^{+}	1.29	1.84
K Linear	1	0.62	1.03	3.13^{+}	0.75	0.25	0.13	0.01	4.49*	1.89	2.89^{+}	0.44	0.10
N Quadratic	1	0.42	0.01	10.51**	0.09	0.52	0.77	0.06	4.33*	0.87	0.01	0.13	0.59
P Quadratic	1	0.17	0.59	3.55^{+}	0.02	0.16	0.02	0.61	4.63*	0.01	4.59*	0.34	0.92
K Quadratic	1	0.50	1.02	3.69^{+}	0.34	0.25	0.03	0.01	4.73*	0.75	3.59^{+}	0.13	0.05
N*P Linear	1	1.83	11.56**	0.09	0.03	0.01	0.12	3.72^{+}	0.17	1.22	5.17	4.35*	0.24
N*K Linear	1	0.01	0.02	2.68	3.25^{+}	2.18	0.66	0.40	0.85	0.13	0.10	0.22	0.37
P*K Linear	1	0.07	0.28	2.26	1.46	3.17^{+}	1.37	0.36	0.10	1.60	0.18	0.38	2.55
Residual MS	13	0.7465	0.0015	0.0765	0.4800	0.0400	0.0110	3.36	869.21	5229.14	20.98	339.59	272.76
Error MS	44	0.1678	0.0010	0.0723	0.0177	0.0112	0.0091	2.26	392.78	680.13	5.23	76.47	198.57

**, Statistically significant at the 0.01 level.
*, Statistically significant at the 0.05 level.
$^{+}$, Statistically significant at the 0.10 level.

Figure 6. Response of leaf N to rate of N (1989).

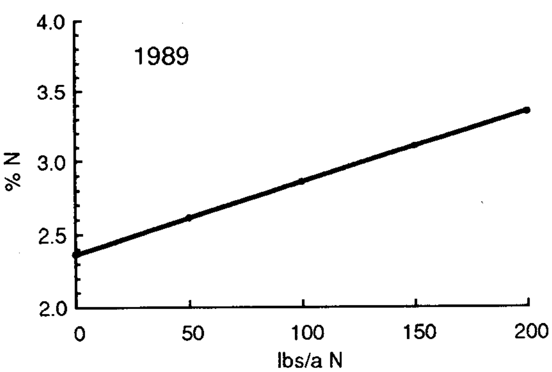


Figure 7. Response of leaf P to rate of P at two N rates (1989).

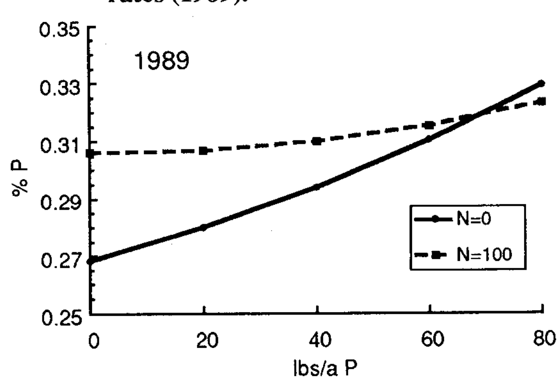


Figure 8. Response of leaf K to rate of N at two P rates (1989).

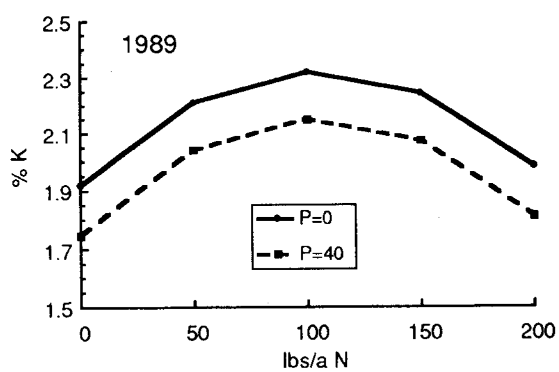


Figure 9. Response of leaf Cu to rate of P at two N rates (1989).

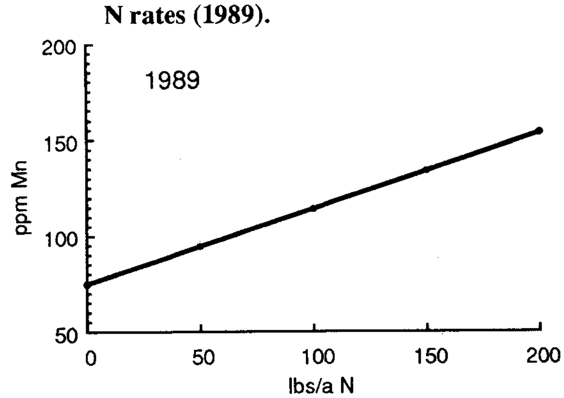
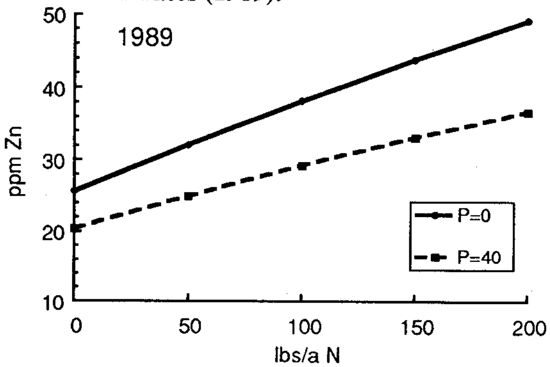


Figure 10. Response of leaf Zn to rate of N at two P rates (1989).



Treatment means and analysis of variance results for 1990 are presented in Tables 5 and 6. As in previous years leaf N was significantly affected by rate of N. However, in 1990 there was a significant quadratic effect and it is illustrated in Fig. 11 where leaf N reaches a maximum at about 150 lb/a of N. Phosphorus was the most significant variable affecting leaf K in 1990 and its effect is illustrated in Fig 12. Within the range of P applied leaf K did not vary greatly. Leaf Mg was affected by both N and K fertilizer and the effects are illustrated in Fig. 13. Leaf Mg decreased with increases in fertilizer K, the magnitude affected by rate of N. Leaf S was affected by each fertility variable in 1990 and the

Table 5. Treatments, average corn yield and leaf composition from the Denmark Fertility Experiment, 1990.

Fertilizer Treatment	Trt#	Reps	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
N P K			Percent						Parts per Million					Bu/a
050-20-030[1/]	1	3	2.58	0.31	1.97	0.66	0.30	0.24	9.7	239	74	13.2	41.1	54.7
050-20-090	2	3	2.59	0.28	2.01	0.80	0.36	0.25	10.8	236	94	13.7	35.8	57.1
050-60-030	3	3	2.26	0.28	1.83	0.69	0.34	0.27	9.0	204	92	11.5	37.0	66.3
050-60-090	4	3	2.76	0.32	1.83	0.83	0.38	0.23	8.6	215	86	13.3	34.8	56.7
150-20-030	5	3	3.36	0.31	1.67	0.84	0.39	0.26	10.9	220	104	16.3	40.6	68.7
150-20-090	6	3	3.05	0.27	1.67	0.68	0.28	0.29	11.0	224	103	15.6	37.4	68.5
150-60-030	7	3	3.30	0.34	1.96	0.82	0.44	0.28	10.0	225	104	15.5	43.6	76.9
150-60-090	8	3	3.07	0.28	1.59	0.67	0.27	0.25	10.1	232	125	17.6	60.9	39.1
100-40-060	9	3	3.13	0.31	1.95	0.74	0.26	0.27	11.5	228	102	17.3	36.8	60.9
000-40-060	10	3	2.38	0.31	1.99	1.09	0.59	0.27	14.7	214	134	14.5	31.5	53.9
200-40-060	11	3	3.37	0.31	1.93	0.83	0.34	0.25	13.1	215	123	17.0	46.5	73.5
100-00-060	12	3	3.34	0.30	2.06	0.63	0.28	0.28	11.2	211	107	17.6	61.2	81.0
100-80-060	13	3	2.88	0.30	1.91	0.62	0.25	0.23	11.2	224	86.2	12.9	34.7	54.3
100-40-000	14	3	2.86	0.28	1.40	0.77	0.45	0.37	9.5	219	120	14.1	50.3	64.9
100-40-120	15	3	3.39	0.31	1.84	0.72	0.24	0.25	9.9	226	98	16.1	43.6	41.0
000-00-000	16	3	2.16	0.29	2.01	0.46	0.22	0.20	8.0	187	58	8.9	29.0	63.0
000-00-120	17	3	1.82	0.24	1.88	0.50	0.18	0.17	8.2	141	33	16.4	27.9	52.7
000-80-000	18	3	1.80	.34	1.58	0.52	0.25	0.18	7.7	189	42	7.9	23.3	55.1
000-80-120	19	3	1.65	0.33	1.98	0.47	0.21	0.18	8.9	153	41	7.6	26.6	63.4
200-00-000	20	3	3.49	0.29	1.47	0.79	0.56	0.29	13.2	212	172	17.3	68.8	41.9
200-00-120	21	3	3.27	0.31	2.08	0.71	0.33	0.25	12.7	202	169	19.2	74.6	43.9
200-80-000	22	3	3.23	0.29	1.46	0.92	0.47	0.25	10.4	238	134	14.8	38.0	54.9
200-80-120	23	3	3.12	0.31	2.03	0.63	0.24	0.24	10.1	206	103	15.1	83.4	56.8

[1/] Fertilizer treatments are lbs/acre of elemental nitrogen, phosphorous, and potassium, respectively.

Table 6. Error mean squares and F ratios measuring the effect of fertilizer rates upon corn yield and leaf composition on the Denmark Fertility Experiment, 1990.

Sources of Variation	DF	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
		F Ratio											
Total	68												
Blocks	2	0.03	2.53+	0.21	1.25	1.87	0.58	2.16	11.72**	0.50	2.58+	1.02	12.11**
Treatments	22												
N Linear	1	18.12**	0.03	0.82	1.51	2.35	20.42**	0.35	6.39*	4.46*	5.36*	1.53	0.01
P Linear	1	0.00	0.46	4.08*	6.82*	2.95+	3.33+	0.002	0.42	0.44	0.11	1.93	0.32
K Linear	1	0.11	0.35	3.12+	0.48	0.46	5.91*	3.26+	0.04	0.15	1.29	1.43	1.48
N Quadratic	1	5.56*	0.01	0.01	0.02	0.13	13.98**	0.70	5.55*	0.05	1.59	0.31	0.01
P Quadratic	1	0.45	0.01	2.41	6.30*	2.61	5.65*	0.01	0.51	0.45	0.02	0.71	0.19
K Quadratic	1	0.34	0.02	3.72+	0.07	0.35	3.24+	3.24+	0.09	0.07	0.05	0.47	2.67
N*P Linear	1	0.03	3.10+	0.64	0.01	1.88	0.16	1.97	0.34	2.34	0.45	0.05	0.19
N*K Linear	1	0.03	1.68	2.45	3.70+	7.80**	0.01	0.39	0.47	0.02	0.69	3.17+	0.01
P*K Linear	1	0.39	0.53	0.56	1.14	0.01	0.33	0.04	0.17	0.01	1.80	2.65	0.03
Residual MS	13	1.311	0.001	0.092	0.540	0.030	0.003	7.51	2036.0	5510.6	40.95	968.16	472.21
Error MS	44	0.164	0.001	0.091	0.024	0.010	0.001	5.39	1127.6	1260.9	13.51	329.15	409.76

**, Statistically significant at the 0.01 level.
*, Statistically significant at the 0.05 level.
+, Statistically significant at the 0.10 level.

effect of N and K are illustrated in Fig. 14. It is not apparent from the data why S should be affected by fertility variables in 1990 and not in other years. Differences in growing seasons and the change in hybrid are possibilities. The only variable affecting leaf Cu in 1990 was N fertilizer and the effect is linear (Fig. 14).

The average change in soil P and soil K as a result of fertilizer applications was determined by regressing the difference between plot soil P and soil K values in 1991 and those in 1988 (1991 values - 1988 values) upon the total amount of P and K fertilizer applied. The resulting linear regression coefficients had values of 0.362 and 0.256 for P and K, respectively. This indicates that for each lb/a of fertilizer P applied, a 0.362 lb/a increase in available P occurred, and for each lb/a of fertilizer K applied, a 0.256 lb/a increase in exchangeable K was observed in the minesoil. Peck et al., (14) found that 4 lb/a of fertilizer P was required to increase the Bray P-1 soil test by 1 lb/a in natural soils.

SUMMARY

Fertility variables significantly affected yield in 1988, but had no significant effect upon corn yield in 1989 and 1990. Fertility variables significantly affected leaf composition each year of the study, but effects were not consistent from year to year. Applied N was the variable most often associated with changes in leaf composition. Yields were lower than might have been expected on natural soils and it is likely that some factor(s) other than N, P and K were limiting. The leaf composition data indicate that plant nutrients were not major limiting factors at observed yields. The change in soil test levels of P as a result of applied P fertilizer indicate that the buildup in soil P in this study is similar

Figure 11. Response of leaf N to rate of N (1990).

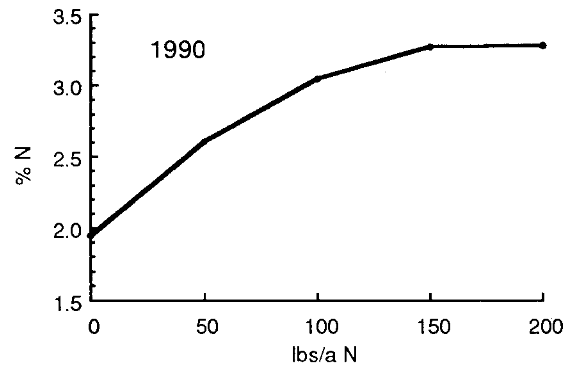


Figure 12. Response of leaf K to rate of P (1990).

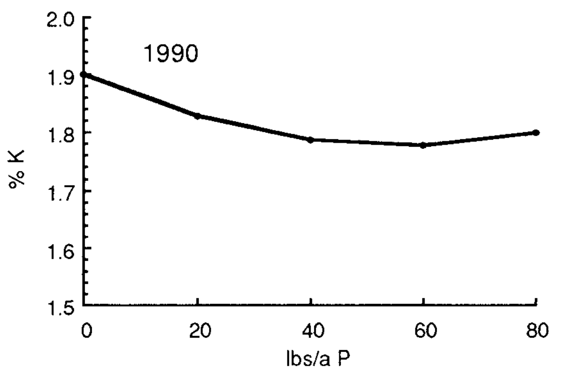


Figure 13. Response of leaf Mg to rate of K at two N rates (1990).

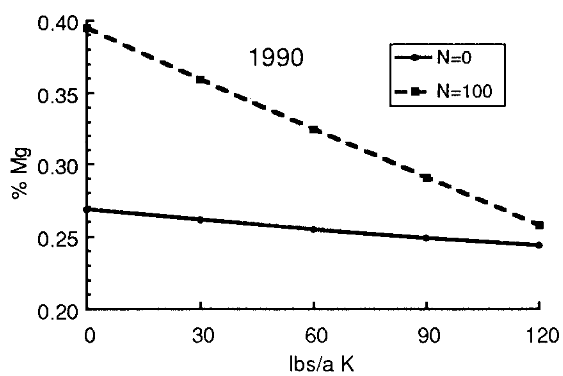


Figure 14. Response of leaf S to rate of N at two K rates (1990).

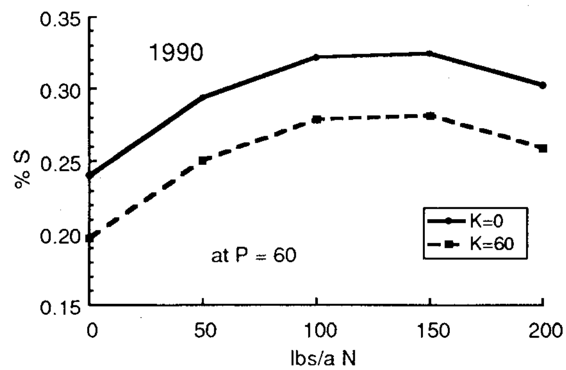
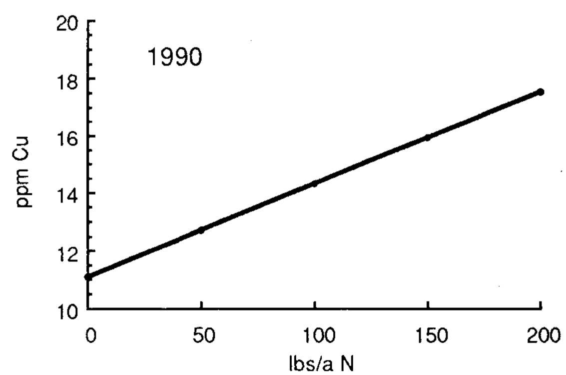


Figure 15. Response of leaf Cu to rate of N (1990).



to that observed in other studies on natural soils.

Corn yields at this site were low compared to those observed on nearby undisturbed soils. It is likely that soil compaction is a major factor limiting yields. Compaction alleviation with a tillage treatment deeper than that affected by the TLG-12 is probably necessary to achieve maximum response to fertility variables. It is probably unrealistic to expect a yield response to an increase in fertility in minesoil if factors such as soil moisture and plant root development are limiting.

ACKNOWLEDGEMENTS

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Row Crop Production in Iowa on Reclaimed Prime Farmland Soil

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Abstract. Since 1979, corn and soybeans have been grown on Clarion loam topsoil restored over its till substratum in Hamilton County, Iowa. The research was undertaken to determine the effect of restored topsoil depth on row crop productivity. Clarion loam (fine-loamy, mixed mesic Typic Hapludoll) was removed to a depth of 12 inches and stock-piled from the 7 1/2-acre site in 1976 in preparation for borrowing approximately 7 feet of subsoil and substratum materials to be used in highway roadbed construction. In 1978, 6 and 12 inches of topsoil were replaced in plots excavated to an equal depth into the substratum in three replicated blocks. A plot without replaced topsoil was also included in each block. The dimensions of experimental area are 360 x 400 feet and the area is 3.31 acres. Without topsoil replacement, corn production has achieved 33 percent of the yearly county average yield. Replacement of 6 and 12 inches of topsoil increased corn yields to 44 and 45 percent of the county average, respectively. Where no topsoil and 6 and 12 inches of topsoil were restored, soybeans have yielded 25, 46, and 52 percent of the county average, respectively. Plant diseases have been observed to be more severe in soybeans in the experimental area, especially where no topsoil was replaced, than on neighboring, undisturbed cropland. Climatic stress resulting from too little or too much moisture has accounted for reduced grain yields compared to county yields in all years and total crop failure in three years. The calculated productivity of this site has included the years where crop failures have occurred.

INTRODUCTION

This paper reports thirteen years of crop production at a site in northcentral Iowa where topsoil was restored following the removal of borrow for highway construction. The research work was supported by the Iowa Department of Transportation. The site was under construction during 1977 and 1978. Clarion loam (fine-loamy, mixed mesic Typic Hapludoll) topsoil occurring at 2 to 5 percent slope was removed to a depth of 6 to 12 inches and stockpiled before borrowing approximately 7 feet of subsoil and substratum materials. Before the last borrow was removed, research plots were planned so that three replicated blocks with three treatments each of restored topsoil could be constructed. These plots were cut to the depth equal to that of the topsoil to be restored; no topsoil, six inches and twelve inches. Each topsoil treatment was 40 feet wide and 400 feet long which yielded a research area that is 360 feet wide and 400 feet long or three and one-third acres. Topsoil restoration was completed in the September of 1978. A subsurface tile drainage system was installed following topsoil restoration. Four-inch diameter tile drainage tubes were installed on an 100-foot spacing, perpendicular to the long dimension of each plot. The research area and its border were fertilized with 100 pounds per acre each of nitrogen (N), phosphate (P_2O_5) and potash (K_2O), chisel plowed, disked, and planted to a winter wheat cover crop.

The substratum at the site is a basal calcareous till with a pH of 7.7. Although available phosphorus and potassium are generally low in the substratum, fertilization from 1978 to 1984 has provided adequate nutrients with current levels being rate high. The topsoil is alkaline with a pH of 7.2 and available phosphorus and potassium are rated high. Soil density was measured from soil cores obtained in 1987 and is reported in Table 1. The density of the restored topsoil is equal to that of the undisturbed Clarion surface soil. The density of the surface 6-inch horizon where no topsoil was replaced is dense, about equal to the subsurface horizon of the undisturbed soil. Finally, the till substratum density in the research plots is greater than that reported for the undisturbed solum from 0 to 60 inches. Substratum densities in excess of 1.70 g/cc will greatly restrict root growth and water and air movement in the soil.

In the spring of 1979, a row crop rotation consisting of alternate years of corn and soybeans was initiated on the site. This is the common crop rotation used in the county. Adapted corn hybrids and soybean cultivars are selected each year and planted as timely as possible. Although the plots are tile drained, internal drainage is slow and field work is usually delayed following heavy rainfall events by an additional 3-4 days compared to adjacent, undisturbed farmland. After the initial fertilization of all plots in the fall of 1978, the plots were fertilized only during the year that corn was grown until 1985. At that time, the plots that had received no topsoil were fertilized with 400 pounds of P_2O_5 per acre. Only N is applied to the corn plots at 150 pounds per acre each year throughout the study. The plots are chisel plowed each year except where a ridge till cropping system was installed in 1990. Both corn and soybeans are planted in rows spaced 30 inches apart.

RESULTS AND DISCUSSION

Crop yields have been greatly affected by weather conditions throughout the 13 years of research. Generally, wet field conditions have delayed field work and planting. Replanting has been required once. Precipitation and temperature data have been compiled from the official Webster City weather station located four miles northeast at the local radio station. These records are presented in Tables 2 and 3. The annual total precipitation for Hamilton County is 30 inches. During the study period, five years had below normal and eight years had above normal precipitation. The most severe drought occurred in 1988 when 18 inches of precipitation was recorded and temperature excesses were recorded as well.

The Clarion soil occurring on 2 to 5 percent slopes has a corn yield potential of 141 to 145 bushels per acre for uneroded and eroded phases, respectively. Soybean yield potentials are 46 and 45 bushels per acre for the same erosion classes. Surface soil thickness is generally 8 inches, subsurface thickness is 20 inches, and the substratum extends to a depth of 60 inches. Clarion soil with 2 to 5 percent slope is a prime farmland soil and constitutes 10 percent of the soils found in Hamilton County. Corn and soybean yield responses to topsoil thickness throughout the study are presented in Tables 4 and 5, respectively.

Although corn has been planted every year during this study, yields were not measured during three of those years (Table 4). Drought injury in 1982 and 1988 was very severe. Corn yields were considered insignificant, less that 5 bushels per acre. In 1990, corn planting was delayed until July 3 and the crop was frozen before it matured. Comparison of the research site with the reported county averages shows that corn grown with no topsoil and 6 and 12 inches of restored topsoil has yielded about 45, 60 and 62 bushels per acre, respectively. Over the thirteen year period, these yields are 33, 44 and 45% of the county average. In one year, 1987, the plots receiving topsoil yielded more corn than the county average for the year. Statistical analysis of the yield data shows a highly significant increase from the addition of topsoil but no significant difference between plots receiving 6 or 12 inches of topsoil.

Similarly, soybeans have been planted every year of the study (Table 5). Soybean yields are not reported for 1982, 1983 and 1988. During each of those years, drought injury was severe. Inspite of a July 4 planting date in 1990, the soybean crop reached maturity but yields were greatly reduced. Over the thirteen year

Table 1. Soil moist bulk density of restored soil treatments.

Restored soil, in	Soil depth interval sampled, inches: 0-6	6-12	12-18	18-24	24-30
	g/cc				
No topsoil					
Average	1.732	1.899	1.874	1.926	1.929
Maximum	1.766	1.974	1.978	2.025	1.996
Minimum	1.693	1.827	1.811	1.850	1.827
6 inches					
Average	1.436	1.657	1.851	1.893	1.901
Maximum	1.562	1.787	1.891	1.941	1.981
Minimum	1.364	1.511	1.750	1.847	1.836
12 inches					
Average	1.412	1.505	1.840	1.929	1.974
Maximum	1.578	1.753	2.070	1.988	2.043
Minimum	1.249	1.329	1.568	1.886	1.921

Clarion (from Soil Survey) Depth, in	Moist bulk density g/cc	Clay Pct
0 - 18	1.40 - 1.45	18 - 24
18 - 36	1.50 - 1.70	24 - 30
36 - 60	1.50 - 1.70	12 - 22

period, soybeans grown with no topsoil and 6 and 12 inches of restored topsoil have averaged about 10, 19 and 21 bushels per acre, respectively. These yields are 25, 46 and 52% of the county average. The yield response to restored topsoil compared to no topsoil is highly significant and the yield increase between 6 and 12 inches of restored topsoil is significant at 0.0205 (PR>F) value.

In 1990, a crop management variable was introduced at the research site. A ridged-till cultivator was used to build ridges upon which soybeans were planted in 1991. Adjacent to these plots were conventionally prepared flat seedbeds. Soybean yields were 28, 16 and 18% greater on ridged than flat seedbeds in no topsoil, 6-, and 12-inch topsoil treatments, respectively. This yield increase was highly significant at 0.0006 PR>F.

The ridged tillage system can overcome some of the near-surface disadvantages. For instance, the ridge is better drained and consequently warms more rapidly in the spring. Even after heavy rainfall, the ridge is not submerged and consequently the soybean plants are not exposed to standing flood waters. One important observation in this study has been that the severity of Phytophthora root rot occurrence has lessened and more plants survive on ridged compared to flat seedbeds. The incidence of Phytophthora infection has always been greatest where no topsoil was restored. Although ridged topsoil plots resulted in greater soybean yields, the incidence of plant disease was less than in those plots with no topsoil.

Table 2. Growing season and annual precipitation and deviation from normal record for the Webster City weather station

Year	May		June		July		August		Annual
	Pcpt	Dev.	Pcpt	Dev.	Pcpt	Dev.	Pcpt	Dev.	Pcpt
	inches								
1979	3	-1	3	-2	6	2	9	6	37
1980	2	-2	4	-1	2	-2	6	2	21
1981	3	-1	7	2	3	-1	4	8	27
1982	8	3	3	-2	6	2	5	1	40
1983	5	1	4	0	8	3	4	0	42
1984	4	0	6	2	6	1	0	-4	35
1985	2	-1	3	-2	1	-3	8	-3	28
1986	4	0	5	1	5	1	3	-1	37
1987	2	-1	3	-1	8	4	6	2	33
1988	1	-2	1	-3	1	-3	3	-1	18
1989	2	-2	5	1	5	0	3	-2	27
1990	6	2	11	7	6	2	2	-2	36
1991	9	5	5	0	2	-2	4	0	42

Table 3. Growing season and annual temperature and deviation from normal record for the Webster City weather station

Year	May		June		July		August		Annual
	Temp	Dev.	Temp	Dev.	Temp	Dev.	Temp	Dev.	Temp
	degrees Fahrenheit								
1979	59	-1	69	0	72	-1	71	-1	45
1980	62	2	70	1	77	4	73	2	48
1981	58	-2	70	1	74	1	70	-2	49
1982	62	2	65	-4	74	1	70	-1	46
1983	56	-4	69	0	77	3	78	7	47
1984	57	-3	70	1	72	-2	73	2	47
1985	64	3	67	-3	72	-1	68	-3	46
1986	61	1	72	3	75	2	67	-4	48
1987	66	6	73	3	76	2	69	-2	51
1988	66	6	74	4	75	2	76	5	48
1989	59	-2	68	-2	74	0	70	-1	46
1990	57	-4	70	1	72	-2	71	0	49
1991	64	3	74	4	74	0	71	0	48

SUMMARY

The topsoil restoration research site at the northcentral Iowa location in Hamilton County is unique because topsoil was restored over substratum into plots cut to the depth to be restored. The substratum was not disturbed below the depth of the cut. Crop yields have varied from greater than the county average to complete failures. Soybean yields have achieved a greater percentage of the annual county average where topsoil was restored than corn. Where no topsoil was restored, corn has yield 33% of the county average yield compared to 25% for soybeans. Soybeans grown without topsoil have exhibited greater incidence of disease than corn.

Throughout the thirteen years of the study, the substratum has remained very dense. The substratum exposed in the surface 6-inch layer remains very dense even though this zone has been tilled every year. Consequently, soil management practices must be used that attempt to avoid the problems associated with dense soil. Recently initiated research using the ridged seedbed practice has overcome a portion of the drainage impediment at the site. Without spring tillage, planting can be carried out at the most opportune time; this lessens some of the risks of delayed planting with its loss of yield potential.

Table 4. Corn yield response to restored topsoil depth.

Year	Restored topsoil depth, inches			County
	0	6	12	average
	bushels/acre			
1979	75.7	136.4	124.8	140.6
1980	75.2	80.1	73.6	125.3
1981	106.0	113.5	126.2	141.1
1982				130.0
1983	18.3	13.7	17.0	104.0
1984	33.5	39.5	41.7	113.6
1985	40.3	31.2	23.5	140.1
1986	68.3	70.4	71.2	146.8
1987	66.1	148.7	156.6	140.9
1988				80.4
1989	58.0	91.3	99.4	154.4
1990				120.3
1991	41.3	57.4	65.7	123.5
Average	44.8	60.2	61.5	127.8
	percent of county yield			
1979	54	97	89	100
1980	60	64	59	100
1981	75	80	89	100
1982	0	0	0	100
1983	18	13	16	100
1984	29	35	37	100
1985	29	22	17	100
1986	47	48	48	100
1987	47	106	111	100
1988	0	0	0	100
1989	38	59	64	100
1990	0	0	0	100
1991	33	46	53	100
Average	33	44	45	100

Table 5. Soybean yield response to restored topsoil depth

Year	Restored topsoil depth, inches			County
	0	6	12	average
	bushels/acre			
1979	19.8	38.8	40.7	40.7
1980	15.3	31.9	29.1	40.1
1981	16.6	29.0	35.5	44.0
1982				37.1
1983				37.5
1984	7.7	14.0	17.0	34.1
1985	12.6	14.1	13.3	40.2
1986	12.5	30.7	34.1	41.5
1987	20.1	28.8	36.4	42.8
1988				24.4
1989	12.4	27.3	32.0	45.9
1990	4.0	12.0	15.8	39.1
1991	14.4	19.4	23.0	40.1
Average	10.4	18.9	21.3	39.0
	percent of county yield			
1979	49	95	100	100
1980	38	80	73	100
1981	38	66	81	100
1982	0	0	0	100
1983	0	0	0	100
1984	23	41	50	100
1985	31	35	33	100
1986	30	74	82	100
1987	47	67	85	100
1988	0	0	0	100
1989	27	59	70	100
1990	10	31	40	100
1991	36	48	57	100
Average	25	46	52	100

Coal Mine Subsidence Mitigation: Effects on Soil and Crop Yields

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Abstract. Longwall coal mining in southern Illinois causes surface land subsidence which can adversely affect agricultural land by creating wet or ponded areas. While most subsided areas show little impact from subsidence, some areas experience total crop failure. Previous studies have found average corn yield reductions of 4.7 to 95%. Coal companies mitigate subsidence damaged cropland by cutting drainage ditches or grass waterways, adding fill material, recontouring the landscape, or a combination of these methods. The objective of this study was to test the effectiveness of mitigation in restoring grain yields to their pre-mined levels. Seventeen sites in Jefferson and Franklin counties, Illinois, were selected for study. The sites represent conventional mitigation techniques on the predominate soils in the area. Corn (Zea mays L.) and soybeans (Glycine max L.) were harvested in 1988, 1989, 1990, and 1991 from mitigated areas and compared to yields from nearby undisturbed areas. Average four year corn yields were significantly (α=0.05) lower than reference areas. There was no significant reduction in soybean yields averaged over the four years. Soil fertility, bulk density, strength, texture, and hydraulic conductivity were measured to identify factors which may be limiting crop yields at mitigated sites. Fill material at most mitigation sites had SiL to SiCL textures, massive structure, and traffic-induced compaction interfaces. Yield reductions at some sites indicate the need for additional mitigation. This research demonstrated that mitigation of subsidence damage can be successful.

INTRODUCTION

The underground coal mining industry of the Eastern Interior Coal Basin is moving towards high extraction mining methods. These methods extract a higher percentage of the coal than conventional room and pillar mining methods. A consequence of longwall mining is immediate surface land subsidence (Gray and Bruhn, 1984). Subsidence from longwall mining is predictable and damage to buildings and other civil structures can be prevented or moderated (DuMontelle et al., 1981). Subsidence effects on agriculture land have been documented in Illinois (Darmody et al., 1989, Guither, 1986, Guither et al., 1985, Guither and Neff, 1983), in the United Kingdom (Selman, 1986), and in Australia (Ham, 1987). These effects include soil erosion, disruption of surface drainage, wet or ponded areas, and reduction of crop yields.

Southern Illinois is characterized by nearly level to gently rolling topography, shallow water tables, and extensive areas of poorly drained, slowly permeable soils (Fehrenbacher et al., 1984). Land subsidence from underground longwall coal mining creates wet or ponded areas which disrupt farming practices, causes low seed germination, and reduces crop growth and grain yields. Darmody et al. (1989) found a 4.7% average reduction in overall corn yields on subsidence affected land in Jefferson, Franklin, and Williamson Counties, Illinois. In the same study, areas classified as moderately and severely affected by subsidence represented 2.3% and 5.3% of the land area and registered 42% and 95% corn yield reductions, respectively.

Coal companies repair or mitigate areas adversely affected by subsidence by cutting drainage ditches or grass waterways, adding fill, recontouring the landscape, or a combination of these methods. Drainage ditches are typically constructed using small tractor-pulled scraper pans. Fill material is either dug from existing ditches, borrowed in the construction of a pond, or taken from high spots in the field. In the last, topsoil is pushed aside using bulldozers or stockpiled using scrapers in both the borrow area and the area to be mitigated. Subsoil from the high spot is used as fill. Topsoil is then returned to both areas. Fill depths typically range from one-half to three feet. For this study mitigation techniques were classified into three types: (1) Ditch, (2) Fill, and (3) Ditch plus fill. The success of mitigation in restoring grain yields is dependant on a number of factors, including the amount and type of mitigation work necessary, the resources and materials available for the job, and the skill of the operators performing the work. Direct measurements on the amount of subsidence or predicted amount of subsidence were not required by the Illinois State Department of Mines and Minerals when mining permits were issued in 1982 and 1983 (Dan Barkley, 1991, personal communication). Consequently, the amount of subsidence at individual research sites is unavailable. Nevertheless, it is intuitive that there may be a relationship between the amount of subsidence and mitigation success.

Cropland reclamation after underground mining is not well documented. However, there are numerous publications on reclamation of cropland after surface mining for coal. Soil compaction caused by large earthmoving equipment used in subsoil and topsoil replacement has been identified as a major factor limiting crop productivity (Fehrenbacher et al., 1982). While the equipment used in subsidence mitigation tends to be smaller, the potential for soil compaction from scrapers excavating and placing fill and from bulldozers used for cutting ditches still exists. Soil compaction causes an increase in soil density and a simultaneous reduction in fractional air volume (Gupta, et al., 1989). Consequently, plant growth is altered due to poor soil aeration, low nutrient and water availability, slow permeability, and mechanical impedance to root growth (Indorante et al., 1981). Fehrenbacher et al., (1982) found significant differences in corn yields and root densities between different soil replacement techniques. Their research demonstrates the importance of sound soil replacement.

The effectiveness of cropland mitigation after longwall mine subsidence on grain yields and soil physical properties has not been documented. The objectives of this research were to: (1) measure the effectiveness of mitigation in restoring corn and soybean yields to pre-mined levels, (2) compare soil physical properties on mitigated soils and nearby undisturbed soils to identify soil physical factors which may be limiting crop yields, and (3) identify effective or deleterious reclamation methods and make recommendations to improve future mitigation work.

MATERIALS AND METHODS

Seventeen sites were selected in Jefferson and Franklin Counties, Illinois, from an earlier study which identified subsidence-affected areas (Darmody et al., 1988). Crop yields and soil physical properties were not measured at all sites in all years due to logistic problems. The sites were in farmers' fields and received varying amounts of subsidence and mitigation. The dominant soil series were Okaw (Fine, montmorillonitic, mesic Typic Albaqualf), Bluford (Fine, montmorillonitic, mesic Aeric Ochraqualf), and Cisne (Fine, montmorillonitic, mesic Mollic Albaqualf). The soils were classified as highly, moderately, and somewhat sensitive to subsidence damage due to their natural drainage and landscape position (Darmody, et al., 1988). A site consisted of the mitigation area, usually no larger than one-half hectare (1.2 acres), paired with an undisturbed reference area within the same field. The fields were planted to corn or soybeans and managed by individual farmers. There was variability between sites in planting dates and other management practices, however, these variables were constant within a paired mitigated and reference site.

Four soil fertility samples were collected during harvest at mitigated and reference areas. A sample consists of a composite of 5 cores taken to a depth of 23 cm. Soil fertility levels were determined by a contract laboratory (Brookside Farms Lab. Asso., Inc. New Knoxville, Ohio 45871). Phosphorus and potassium levels were determined using a Mehlich 3 extractable procedure and inductively coupled plasma (ICP) spectrometry. Soil pH was determined by a 1:1 paste method and an electrode. Organic matter was estimated by a modified organic carbon combustion method at 350° C (Mark Flock, 1991, personal communication).

Corn and soybeans were hand harvested in the fall of 1988, 1989, 1990, and 1991. Yield estimates were based on the grain weight from sampling units of four 6.1 m long rows from mitigated and reference areas. Corn yields were corrected to 15% moisture and soybeans to 13% moisture. Since sites consisted of one mitigated and one reference area, true experimental error did not exist. A general linear model was used with the sums of squares partitioned out for site and treatment with the site by treatment within year interaction being used to test for treatment effects. The residual sums of squares reflect the sampling error for the experiment. A least significant difference (LSD) was calculated using the site by treatment within year interaction term as the error mean square.

Three undisturbed soil cores 7.62 cm in diameter were collected at mitigated and reference sites to a depth of 1.2 m using a Giddings hydraulic coring machine. The cores were divided into 22 cm segments from which a 7.62 cm long sample was taken from approximately the middle of the segment. The top two segments (0-22 and 23-44 cm) were discarded to avoid the plow layer and the E horizon. The samples were waxed into pre-cut PVC tubing to seal side walls and to keep the samples moist until analysis. Saturated hydraulic conductivity was determined by a standard constant head laboratory technique (Klute and Dirksen, 1986). After hydraulic conductivity determinations, the cores were placed in low pressure suction funnels and desorbed from saturation to field capacity. Bulk density by the core method (Blake and Hartge, 1986) and particle size analysis by the hydrometer method (Gee and Bauder, 1986) were determined from the soil cores.

Soil strength was measured in situ to a depth of 110 cm using a constant rate cone penetrometer (Hooks and Jansen, 1986). Five samples were taken in mitigated and reference areas. A sample consisted of the mean of two replications. The 110 cm data profiles were separated into five 22-cm segments for statistical grouping. A mean penetrometer resistance value was calculated for segments three, four, and five. The means of paired segments were compared using an LSD (α=0.05) test. Segment one was discarded because of disturbance from annual cultivation and segment two was discarded because it coincides with the E horizon of the natural soil which was dryer than the same segment in fill.

RESULTS AND DISCUSSION

Soil Fertility

Soil test results for pH, organic matter, phosphorus, and potassium are presented in Table 1. Soil fertility could be adversely affected by subsidence mitigation in two ways. First, recontouring could expose less fertile subsoil and remove fertile topsoil. Second, fill material could be deficient in major or minor plant nutrients or organic matter, or could contain excessive amounts of sodium. Coal company reclamation supervisors report that topsoil is typically removed before adding fill and then replaced upon completion of the work. Organic matter estimates from fertility data confirm this for most sites. Since topsoil is mixed and replaced by reclamation activities, no differences in fertility levels are expected between reference and mitigated areas.

Phosphorus and potassium levels at some sites were lower than recommended for optimal yields for the soils studied (Illinois Agronomy Handbook, 1991). However, since soil fertility levels at mitigated areas were equal to or higher than nearby reference areas, differences in available phosphorus or potassium should not account for yield deficiencies in mitigated areas. Similarly, secondary nutrients analysis show no significant differences between reference and mitigated areas. Loss of applied nitrogen to corn crops due to saturated soil conditions in mitigated areas is a possible limiting factor. This factor was not tested, however, nitrogen deficiencies evaluated by visual inspection where not observed throughout the growing season.

Yield Response

Yields averaged over all sites for corn and soybeans are presented in Table 2. Average corn yields were significantly lower at mitigated areas in 1990 and 1991 and significantly lower when averaged over the four year study. Soybean yields were significantly higher in 1989 and significantly lower in 1991 but not statistically different averaged over the four years. During the drier growing season of 1988, crops in the mitigated areas appeared to have benefited from the extra water collected and held by subsidence troughs. In contrast, a wet spring in 1990 precluded planting or caused low seed germination in these same areas. Corn plant counts were significantly lower in 1990. Corn ear counts were significantly lower in 1990 and 1991, and significantly lower averaged over the four year study. Hence, both low plant stands and plant stress resulting in low ear counts account for lower yields in mitigated areas. The apparent better response of soybeans than corn to mitigation is attributed, in part, to a later planting date under typically better soil temperature and moisture conditions.

Crop yields at individual sites varied widely within a given year. As a consequence, "best case" extremes or sites where mitigated yield was higher relative to reference yields were usually not statistically different (Table 3). In contrast, most "worst case" extremes are significantly different. This indicates productivity has been returned to pre-mined levels at some sites, while at other sites significant yield reduction can still occur after mitigation. Table 4 shows crop yields for different mitigation methods. Ditch type mitigation showed statistically similar yields to reference yields. In contrast, adding fill or ditch plus fill mitigation was unsuc-

Table 1. Grand mean of soil test results.

Treatment	%O.M.	pH	P(lbs/a)	K(lbs/a)
Reference	2.4	7.0	57	198
Mitigated	2.6	6.8	59	216
Difference	+0.2	-0.2	+2	+18
Recommended§		6.0-6.5	50	260

§ Illinois Agronomy Handbook, 1991.

Table 2. Crop yields at subsidence mitigation research sites.

Crop	Treatment	1988	1989	1990	1991	Mean
		- - - - - - - - -	- - - -	bu/a	- - - -	- - - - - - - - -
Corn	Reference	95	125	112	106	110
	Mitigated	96	116	79	74	89
	Difference	+1	-9	-33*	-32*	-21*
	LSD	7	17	15	24	12
	n§	6	7	11	4	28
Soybean	Reference	26	29	28	31	29
	Mitigated	25	36	24	25	27
	Difference	-1	+7*	-4	-6*	-2
	LSD	2	6	6	5	3
	n	7	3	3	10	23

* significantly different (α=0.05)

§ mean of n sites.

cessful in restoring pre-mined corn yields. Both ditch and fill mitigation were successful in restoring soybean yields to pre-mined levels whereas ditch plus fill was unsuccessful.

Soil Physical Condition

Soils at selected research sites were characterized to identify factors which may be limiting yields. Typically, mitigated sites were characterized by massive or platy soil structure in added fill material. Soil texture of fill and natural soil ranged from silt loam to silty clay. Fill material usually had less clay than the natural soil. Table 5 shows mean values for bulk density, penetrometer resistance, and laboratory saturated hydraulic conductivity. Low hydraulic conductivity values were observed in both mitigated and reference areas and are attributed in part to the medium to fine textured soil and fill material. Both reference and mitigated sites showed variability in hydraulic conductivity with depth. In mitigated areas, massive structure and compaction left by earthmoving equipment were observed in the soil cores, and contributed to low hydraulic conductivity. Also contributing to low hydraulic conductivity values in mitigated cores were inclusions of foreign material (i.e. wood, weeds) in the fill. In contrast, higher hydraulic conductivity values in reference soils are attributed to the natural moderately strong and strongly developed soil structure and to partially filled channels and voids left by crayfish and other soil fauna or plant roots. At many sites the hydraulic conductivity was only slightly different between reference and mitigated areas. All values are within the moderately low to moderately high Soil Conservation Service (SCS) conductivity class (U.S. Dep. Agriculture, 1991). Overall, there

Table 4. Overall yields for different mitigation methods.

Treatment	Corn	Soybean
	- - - - - - - - bu/a - - - - - - - -	
Reference	110 a§	29 a
Ditch	97 ab	28 a
Fill	76 b	29 a
Ditch+Fill	89 b	23 b

§ Means within columns followed by the same letter are not significantly different (0.05).

Table 3. Crop yield extremes at individual sites.

Crop	Year	Site	Reference	Mitigated	Difference
Corn			- - - - - - - - - - - - - -	bu/a - - - - - - - - - - - - - -	
Worst case	1988	8	105	84	-21*
	1989	2	158	107	-51*
	1990	3	122	23	-99*
	1991	8	111	62	-49*
Best case	1988	6	84	116	+32*
	1989	13	74	91	+17
	1990	11	79	75	-4
	1991	1	111	109	-2
Soybean					
Worst case	1988	9	36	28	-8*
	1989	6	30	35	+5
	1990	14	32	15	-17*
	1991	15	37	20	-17*
Best case	1988	2	32	32	0
	1989	7	33	42	+9
	1990	8	33	36	+3
	1991	11	39	44	+5*

* significantly different (0.05)

Table 5. Soil parameters averaged over 45-100 cm depth

Mitigation Method	Bulk Density (g/cm^3)		Penetrometer Resistance(MPa)		Hydraulic Conduct.(cm/d)		n§
	REF*f*	MIT	REF	MIT	REF	MIT	
Ditch	-¶	-	1.6	2.3	3	7	1
Fill	1.48	1.41	2.0	2.3	21	18	4
Ditch+Fill	1.49	1.36	1.7#	1.9#	19	11	6

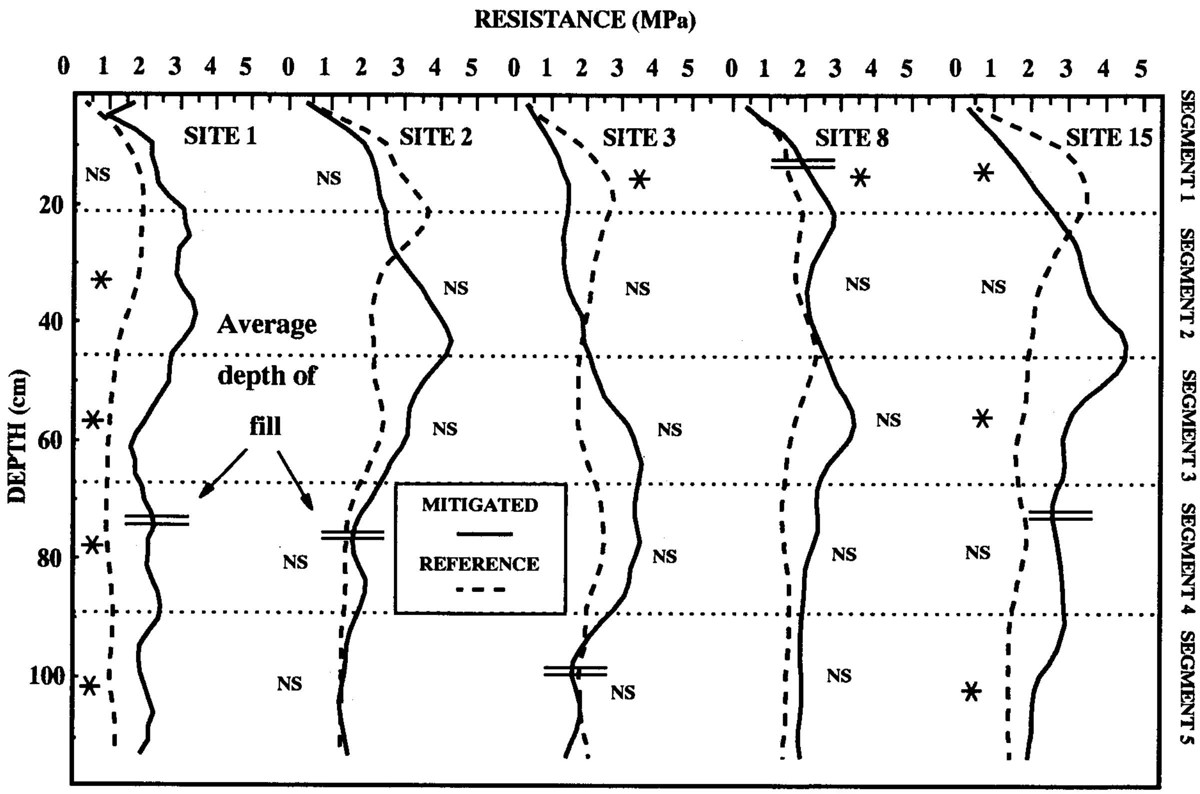
§ Mean of n sites with 9 determinations per site, *f* REF for Reference, MIT for Mitigated, ¶ No sample, # Mean of 4 sites.

appears to be little difference between mitigation method on hydraulic conductivity. In summary, soil hydraulic conductivity is often reduced as a result of mitigation, however, the change is not of great significance because of the moderately low permeability of the natural soil.

The lack of soil structure in fill material did not significantly change the bulk density from reference soils (Table 5). This is due in part to similar textures between mitigated and reference areas. Overall, mean bulk density values for both fill and ditch plus fill mitigation tend to be only slightly lower than reference soils. Hence, soil compaction as identified by higher bulk density does not appear to be affecting yield differences between mitigated and reference areas. It is possible that the sampling density was not great enough to detect changes in bulk density. Although the structure was massive in filled areas it was not necessarily highly compacted throughout. Compaction was mainly in traffic interfaces which may not have been sampled. Lower bulk densities were observed at sites which were reclaimed during dry conditions.

Penetrometer resistance measurements were taken in late spring when soil water content was approximately at field capacity. Soil compaction from reclamation was detected at sites 1, 2, 3, 8, and 15 (Figure 1). Prominent points (sites 2 and 15 at 45 cm) in the penetrometer profile identify traffic or scraper lift faces. These interfaces of high compaction disrupt internal drainage which may result in prolonged soil saturation. Mean values from selected soil depth segments were compared (LSD 0.05 level). Figure 1 shows that most mitigated and reference segment means were not statistically different. Site 1 is an exception, with higher soil strength below the depth of tillage. Root restricting soil strength values depend on soil texture, structure, moisture content, and method of measurement and therefore do not lend to direct comparison from other studies. Penetrometer resistance values in the range of 2 to 2.5 MPa have been identified as potential root restricting values (Taylor and Burnett, 1964). These values are exceeded at some sites and may be causing root restriction. However, in most cases the mitigated values are statistically indistinguishable from reference areas. Overall, penetrometer resistance is higher for all mitigation methods (Table 5).

Figure 1. Penetrometer resistance profiles of mitigated and reference areas. Mean of 10 determinations at each site.



*** significantly different (0.05 level)**
NS non-significant

SUMMARY AND CONCLUSIONS

Successful mitigation of land adversely affected by longwall mine subsidence in southern Illinois is dependent on adequate water drainage. Level topography and naturally poorly drained soils makes this task difficult. Results from four years of yield sampling show mitigation of subsidence-affected areas can be effective in restoring yields to pre-mined levels for soybeans but not for corn. In a previous coal mine subsidence study in southern Illinois, Darmody et al. (1989) found a 42% reduction in corn yields for areas moderately affected by land subsidence and a 95% reduction in yields for severely affected areas. This study found overall yield reductions of 19% for corn and 7% for soybean in mitigated areas (Table 2). This research showed that all types of mitigation (ditch, fill, and ditch plus fill) can be successful. Rainfall and other factors may compound yield response at any site to cause significant yield reductions regardless of mitigation method. Trends in this research relative to the number of sites studied suggest ditching is more successful than ditching plus fill or fill only. Site specific factors such as the amount of subsidence damage, and hence the amount of mitigation necessary, and field/landscape characteristics may bias ditching success rate. For example, ditching may be done when subsidence creates a gentle and continuous trough, as opposed to a localized depression or "pit" which would require fill. The disadvantage of ditch mitigation is that waterways in fields take land out of production and require maintenance.

Results from this study indicate only small overall changes in soil physical properties between mitigated and reference soils. Bulk density and saturated hydraulic conductivity were lower while penetrometer resistance was higher on mitigated areas. These small differences in soil properties are independently unlikely to affect crop yields. Field inspections revealed water drainage was inadequate for crop growth at some sites.

One must keep in mind that mitigated areas are very small in size and that a small decrease in yields on one-half hectare will not significantly reduce overall field yields. However, it is important that mitigation is attempted on all mine subsidence damaged agricultural land not only from a productivity standpoint, but also to prevent associated agricultural problems such as weed and pest control and to maintain normal field patterns for planting and harvest.

The results of this research indicate that the following practices may improve mitigation: 1) reduce soil compaction by working soil and adding fill when the soil is dry, 2) minimize traffic and use low ground pressure equipment on soil and fill, 3) apply deep tillage during and after mitigation work to alleviate compaction interfaces, 4) provide better water drainage by excavating existing drainage ways, and 5) add sufficient depths of fill to low areas. In addition, adding drainage tiles to mitigated areas may improve mitigation success. Drainage tiles are not commonly used in southern Illinois due to low soil permeability and siltation problems in high sodium soils. The Illinois Drainage Guide (1984) reports that a single subsurface drain with surface inlets may be more economical than surface ditches for depressions in these soils. In non-compacted fill material, a subsurface tile may provide adequate drainage for crop growth, provided an outlet is available.

As longwall coal mining in this region of productive agricultural soils increases, the need for effective reclamation is important to maintain the agricultural viability of the region.

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The Effects of Coal Mine Subsidence on Soil Macroporosity and Water Flow

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Abstract. Planned coal mine subsidence is increasing as more efficient methods of underground extraction are used. Unlike room and pillar mining, these methods extract most of the coal in a panel. Because no coal is left to support the roof, subsidence occurs over the mined out panel causing cracks to form in the soil.

A field study using Rhodamine B dye and bromide tracers was conducted to determine if subsidence fractures remain in the soil and contribute to increased preferential flow. The dye and Br^- solution was applied with 0.6 m of head to the soil. The soils were later sampled for Br^- and photographed to record dye distribution. Horizontal planes of the soils were excavated to expose the sampling surfaces. Image analysis was used to quantify the pre and post subsidence dye patterns.

Bromide distribution was inconclusive for predicting greater preferential flow after subsidence. However, dyed subsidence cracks were recognizable to 1.6 m depth in the soil above the mine panel edge. This zone is characterized by tensional forces in the soil which allows the cracks to remain open. Of all the trials, the solution at the panel edge site drained the fastest (less than 1 day, as compared to 4 to 7 days for the others). The mine panel center had no visible cracks remaining because the cracks closed completely due to compressional forces.

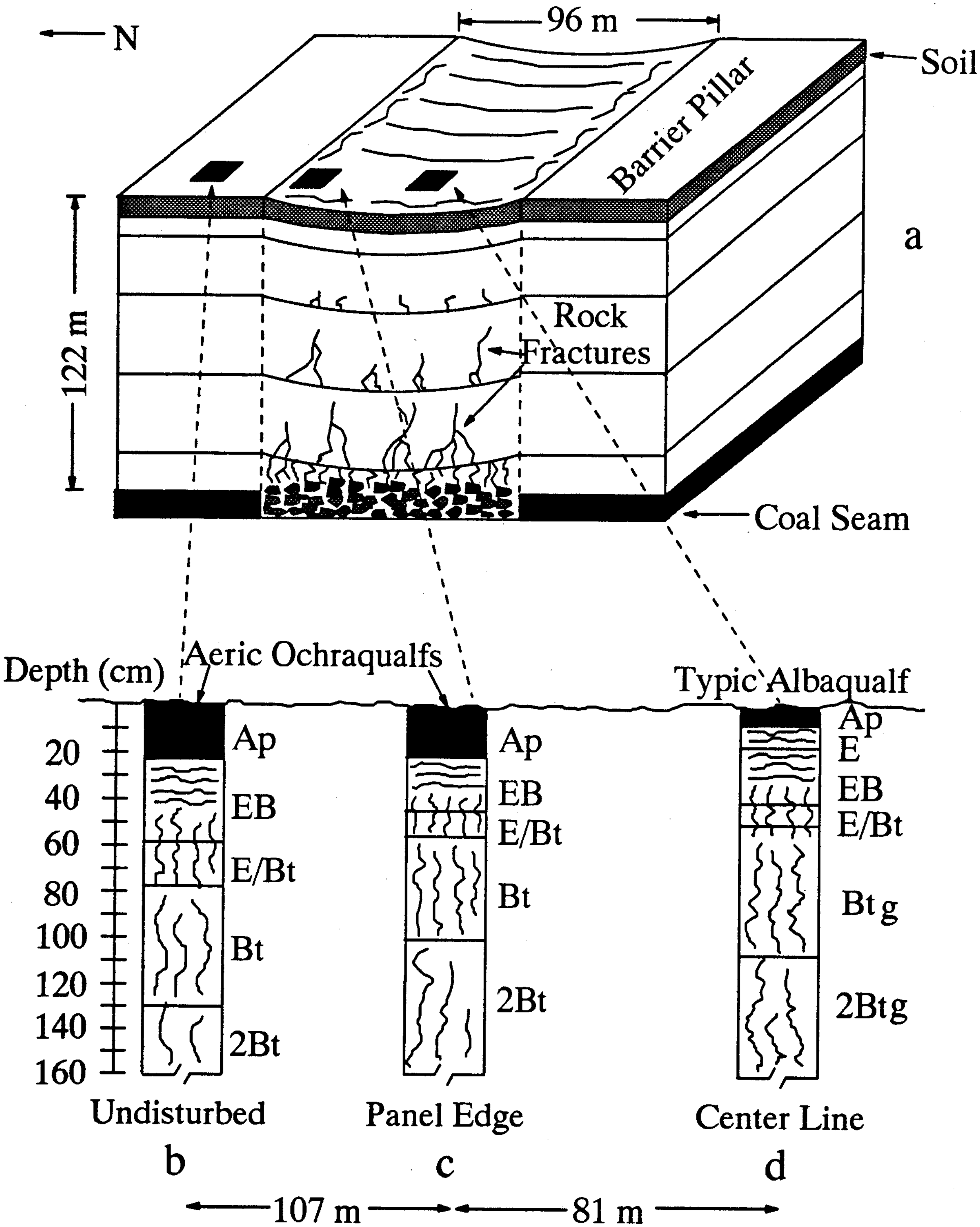
The results indicate that subsidence cracks remain in the soil along the mine panel edge eight months after subsidnece. Additionally, preferential flow was shown to be enhanced at this site following subsidence. However, evidence of this is lacking for the panel center. Further research is needed to determine if groundwater quality changes occur as a consequence of subsidence cracks along the mine panel edge.

INTRODUCTION

The coal mining industry in southern Illinois is adopting longwall (LW) mining as a new and more economical method of underground coal extraction (Darmody et al., 1989). Previous methods involving room and pillar mining left approximately 50% of the coal behind to support the overburden. Longwall mining recovers 100% of the coal in a panel and causes immediate subsidence of the overlying strata (Gray and Bruhn, 1984). Surface subsidence between 0.5 and 2.0 m is typical for Illinois and is dependent on the mining depth, height of the extracted coal seam, and the width of the mine panel (Bauer and Hunt, 1982) (Fig. 1). In LW mining all the coal is removed in panels as much as 200 m wide and 2000 m long resulting in immediate subsidence behind an advancing mining front. Besides the advantage of a higher coal extraction rate, this method of mining averts temporally and spatially random subsidence associated with room and pillar mining. This allows planning for mitigation of subsidence impacts. The elongate depression produced by subsidence is referred to as a "trough" (Bauer and Hunt, 1982). Soil cracks typically form at the trough edges. Although soil cracks up to 0.5 m wide have been observed, the majority are less than a few cm in width. The transverse cracks (Fig. 2) close as the dynamic subsidence wave passes. Longitudinal cracks, however, may remain open until surface processes close them (Van Roosendaal et al., 1992).

One goal of the project was to evaluate the potential of these subsidence cracks to enhance solute movement through the solum. Soils that exhibit strong preferential flow are said to have a biphasic flow regime that allows for rapid flow through larger pores while the water in fine pores remains relatively immobile (Sollins and Radulovich, 1988). As a consequence, fertilizers, pesticides, and other pollutants that are applied at the surface or which are not adsorbed within the soil matrix may be transported into the groundwater (Thomas and Phillips, 1979; Smith et al., 1985). Little information exists on the near surface alteration of water flow as affected by coal mine subsidence. The objective of this research was to measure the effects of coal mine induced subsidence on soil macroporosity and water flow.

Figure 1. Schematic showing subsided panel (a) and soil horizon designations and locations of; (b) undisturbed; (c) panel edge; and (d) center line plots.



MATERIALS AND METHODS

Site Description

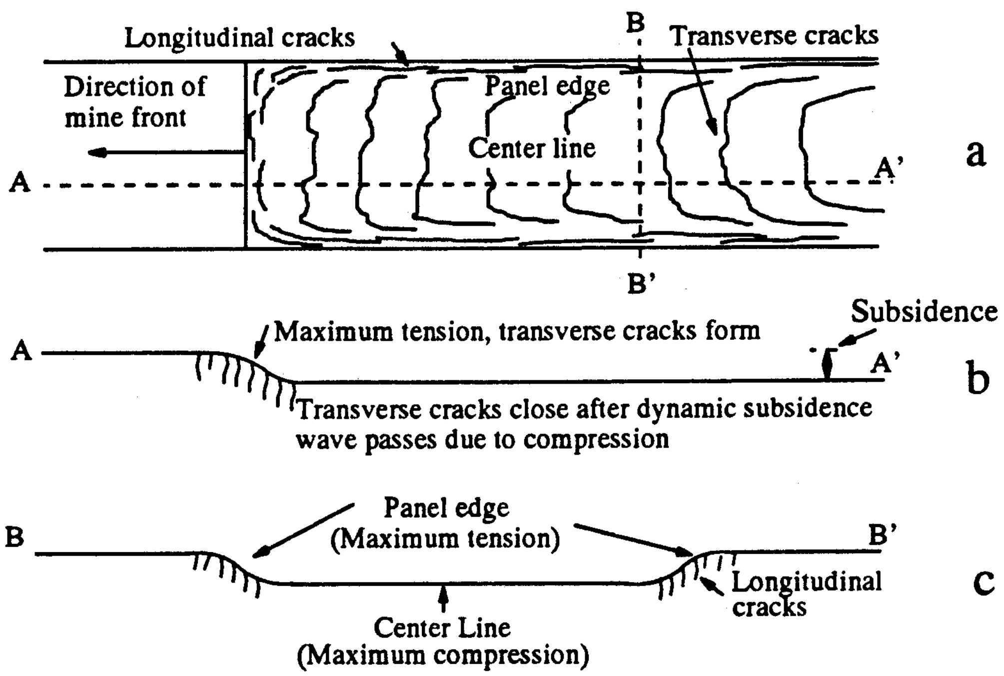
The study area is located in northwestern Saline County, Illinois on a gently rolling Illinoian age till plain. The soil developed under deciduous forest, however, currently it is used for row crop and small grain production. The Herrin Coal seam (1.8 m thick) that underlies the research site was mined at a depth of 122 m. Illinoian age glacial deposits approximately 8 m thick overlie Pennsylvanian age shales and argillaceous sandstones (Van Roosendaal et al., 1990). A loess mantle approximately 60 cm thick overlies the till (Fehrenbacher et al., 1984). The soil series at the study site were Bluford silty clay loam (fine, montmorillonitic, mesic Aeric Ochraqualf) and Wynoose silty clay loam (fine, montmorillonitic, mesic Typic Albaqualf) (Fehrenbacher et al., 1984). Both Bluford soils have a characteristic E/Bt horizon with bleached prism faces which overlies a weak fragipan. The Wynoose soil does not have as well expressed fragic characteristics.

Three pedons were selected to investigate the subsidence effects. Two of the pedons were located above the mine panel edge and center line (Fig. 1c and 1d). An undisturbed or control pedon was located slightly outside the subsidence affected zone (Fig. 1b).

Dye and Tracer Solution

The subsidence induced cracks were characterized using an absorbing dye and an anionic tracer. In August 1989 the three pedons received a solution of saturated Rhodamine B dye and KBr (0.5 g L^{-1}) with a solution head of 60 cm. The solutions were applied in 1.0 by 1.0 m bottomless tanks which were driven into the soil to a depth of 10 cm. Rhodamine B was used to show if subsidence cracks remain after their apparent closure at the soil surface. The dye has a strong visual contrast to the soil matrix and has been used successfully by others (Anderson and Bouma, 1973; Sollins and Radulovich, 1988). Bromide (0.5 g L^{-1} KBr) was used as a conservative tracer to compare water flow between pre and post subsidence (Germann et al., 1984; Onken et al., 1977). Subsidence occured in December of 1989. In August 1990 the procedure was repeated in adjacent pedons. Most of the Ap horizon was scraped off at each site before driving the tanks into the soil. This was done to prevent leakage of the solution outside the tanks into the friable Ap horizon, and to prevent excessive adsorption of the dye by organic matter. The tanks were carefully filled to avoid physically dispersing the exposed soil surface.

Figure 2. Schematic of a longwall mine panel: (a) overhead view of advancing mine face and cracks, (b) longitudinal side view, and (c) cross-sectional view.



Excavation and Sampling

One week after the dye application, the tanks were removed and trenches were dug on two sides to a depth of 3 m. The trenches facilitated excavation of horizontal planes below the tanks. Similar excavation schemes have been used by Logsden et al. (1990) and Ghodrati and Jury (1990). Incremental planes were exposed, smoothed with a scraper, and cleaned with a vacuum to remove debris. Photographs of each layer were taken of a centered 70 by 50 cm sampling area. After a layer was photographed, soil samples (2.5 cm diameter by 1.0 cm deep) of the sampling area were taken in a grid with 48 points for bromide determination. A grid was used to compare preferential movement of Br^- and dye (Seils, unpublished). Bromide was measured using an ion specific electrode (Owens et al., 1985). The lower detection limit was 2.6 mg $Br^- \cdot kg^{-1}$ soil. Both the soil and surface groundwater background Br^- concentrations were below the detection limit. Between 10 and 12 planes were sampled and photographed per plot to depths ranging between 130 to 180 cm. The depth of sampling on the pre-subsidence plots was determined by the absence of dye. However, during post subsidence sampling, lower depths were sampled to determine if Br^- had moved deeper in the profile than the dye. The distance between planes increased with depth as the variation in dye distribution decreased.

Characterizing Dye Distribution

Image analysis (JAVA video analysis software; Jandel Corporation, Corte Madera, CA) was used to quantify the dye patterns. Dyed areas of each plane were hand traced from projections of 35 mm color slides. This was necessary because a concise threshold between stained and nonstained soil could not be obtained from the original slides during image analysis. Dark clay and organic coatings, roots, iron/manganese concretions, etc., were not discriminated from dyed areas. A proper contrast was obtained with the hand tracings. Each plane was analyzed for percent dye area and number of dyed objects, and an apparent object size threshold of 0.03 cm^2 was obtained. Smaller dye stains may have been present but were not included in the image analysis.

Field Measurements

Three Uhland ring samples were collected from each horizon of the three study pedons (Uhland and O'Neal, 1951). Saturated hydraulic conductivity was determined using the constant head method (Klute and Dirksen, 1986). The samples were also used to measure bulk density (Blake and Hartge, 1986). Shear strength was measured with a hand held torvane sampler.

RESULTS AND DISCUSSION

Dye Movement

Dye patterns of all trials revealed greater preferential flow deeper in the profile (Fig. 3). Below the E/Bt horizon, flow was restricted to prism faces and larger macropores. This was observed during excavation, where the faces of larger aggregates were heavily stained whereas the interior contained little dye. The dye that did penetrate the interior of aggregates was due to flow via macropores which were easily observed.

The panel edge plot, Fig. 3b, shows easily recognizable dyed subsidence cracks. The panel edge (Fig. 1c) experiences tensional forces during subsidence due to the induced relief as the panel subsides (Van Roosendaal et al., 1992). Soil cracks which form along this zone occur at angles between 45 and 90 degrees relative to the advancing mining front (Fig. 2). The cracks are more clearly defined with depth, and extend well into the Bt horizon. As subsidence proceeds, a more significant fracturing occurs in these lower depths due to the greater bulk density, shear strength, and stronger consistence with depth (Table 1). These soil properties as well as the absence compressional forces prevent the cracks from closing. Immediately after subsidence fractures were observed at the surface along the panel edges. However, at the time of the solution application (eight months after subsidence) the surface fractures could not be seen. Near the surface, the cracks lose their distinctiveness after time because the soil is more friable, which allows for infilling of the fractures by natural processes.

In the post-subsidence experiment, the solution at the panel edge infiltrated in the shortest time (less than 1 day) as compared to the other plots (4 to 7 days). It is evident that the panel edge zone lacks sufficient compressional forces to completely close the fractures during the period of the study. Dye patterns of the center line (Fig. 3c) do not reveal cracks. Cracks that form along this zone form parallel to and behind the advancing mining front (Fig. 2). As the mining front advances beyond a given point in the center line, compressional forces are generated that tend to close the cracks. The lack of soil cracks along the center line may be due to either (1) the cracks closed completely due to compressional forces in this zone, or (2) the sample area did not include a subsidence crack. It is likely that the cracks closed completely due to compression. Surface cracks were found to be about 1 m apart at the panel edge. No cracks were observed at the center line during post subsidence excavation.

Figure 3. Dye patterns of pre- and post-subsidence trials.

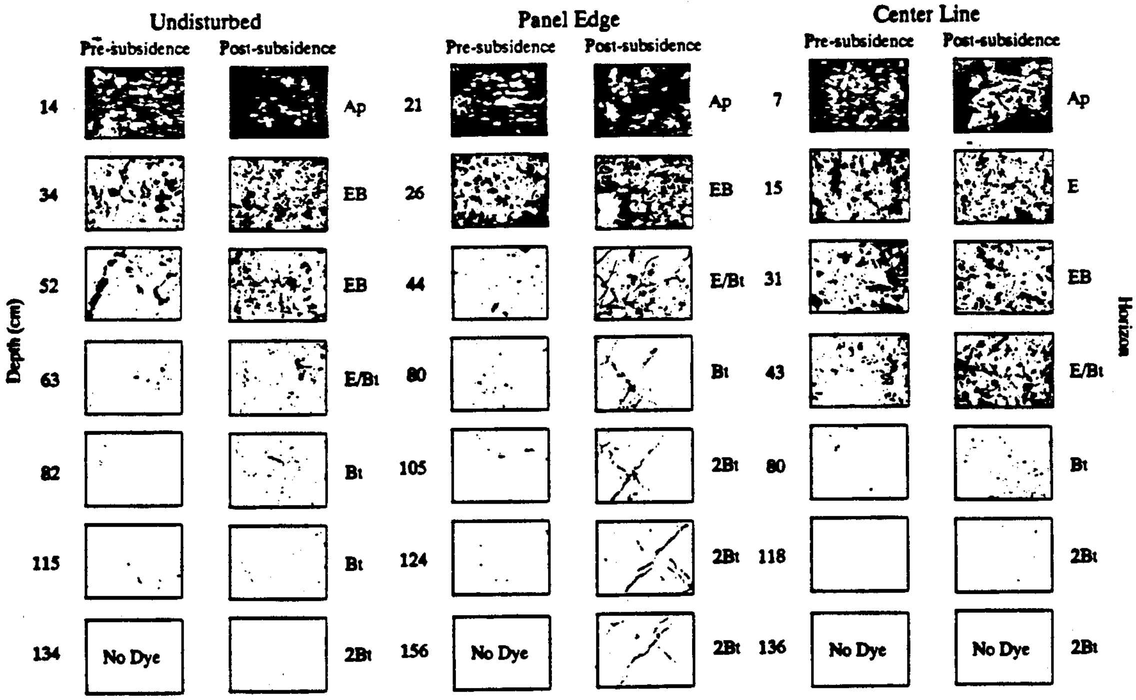
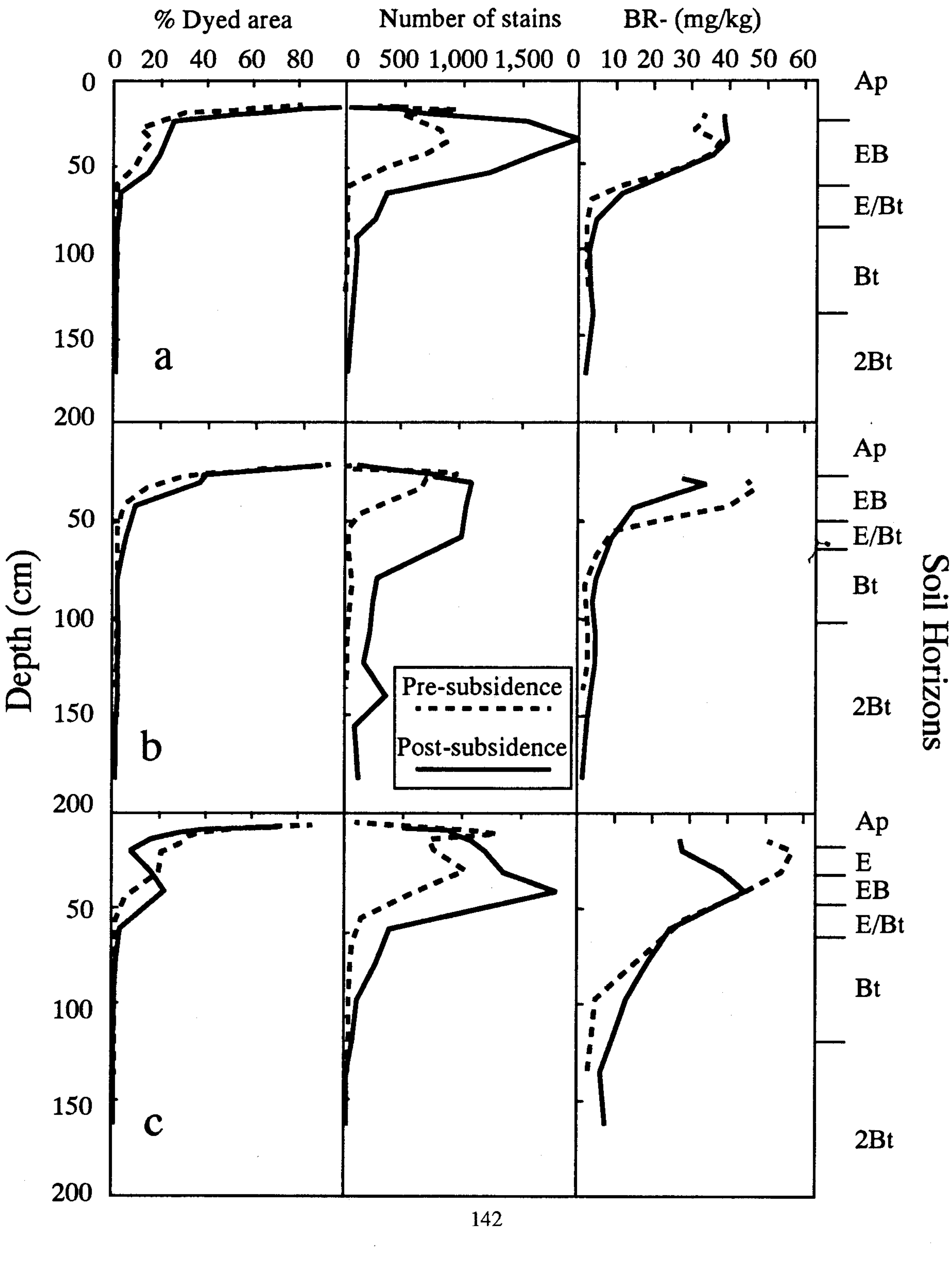


Table 1. Soil bulk density, shear strength, and consistence of the study plots.

Site	Horizon	Depth	Bulk Density	Shear Strength	Consistence
		(cm)	(g/cc)	(kg/cm^2)	
Undisturbed	Ap	0-24	1.50	0.41	Friable
	EB1	24-34	1.50	0.46	Friable
	EB2	34-50	1.46	0.41	Firm
	EB3	50-59	1.47	0.41	Firm
	E/Bt	59-78	1.57	0.67	Firm
	Bt1	78-107	1.53	0.60	Firm
	Bt2	107-130	1.58	0.65	Firm
	2Bt3	130-168	1.66	0.51	Firm
	2Bt4	168-186+	1.65	0.43	Friable
Panel Edge	Ap	0-21	1.47	0.31	Friable
	EB	21-43	1.53	0.31	Friable
	E/Bt	43-53	1.60	0.38	Firm
	Bt1	53-72	1.52	0.61	Firm
	Bt2	72-98	1.57	0.42	Firm
	2Bt3	98-122	1.56	0.42	Firm
	2Bt4	122-140	1.55	0.38	Firm
	2Bt5	140-195+	1.62	0.48	Friable
Center Line	Ap	0-8	1.26	0.39	Friable
	E	8-18	1.38	0.37	Friable
	EB1	18-27	1.44	0.38	Friable
	EB2	27-42	1.41	0.39	Friable
	E/Bt	42-51	1.53	0.37	Firm
	Bt1	51-91	1.47	0.56	Firm
	Bt2	91-108	1.49	0.56	Firm
	2Bt3	108-125	1.54	0.49	Firm
	2Bt4	125-176	1.65	0.61	Firm
	2Bt5	176-192+	1.64	0.56	Friable

Profiles of percent dye area, number of dye stains, and average Br ⁻ concentrations with depth are presented in Fig. 4 for the three plots. All plots show an increase in the number of dye stains during post subsidence sampling. Since both the control plot and the subsided plots showed an increase in dye stain numbers, subsidence effects are not likely the cause of the increased number of stains above the panel edge and center line plots. Differences in soil conditions between pre and post subsidence likely contributed to the in-

Figure 4. Comparisons of % dyed area, number of dye stains, and bromide distributions among pre- and post-subsidence trials: (a) undisturbed, (b) panel edge, and (c) center line.



crease in dye stain numbers for all three plots. Fig. 5 shows profiles of percent soil moisture of the three plots for pre and post subsidence. All plots show greater moisture above the 110 cm depth during post subsidence. Greater soil moisture allowed the infiltrating dye to stay in suspension longer, which decreased the sorption of the dye on the soil particles. A result of this was a greater number of stained pores deeper in the profile.

All plots show little differences in the percent dye coverage (Fig. 4) between pre and post subsidence. Also, there is no discernable relationship between subsidence and increases in hydraulic conductivity of the panel edge and center line pedons as measured with the Uhland rings (Fig. 6). This is because the undisturbed plot showed dissimilar profiles of hydraulic conductivity for the pre and post subsidence trials which indicates

Figure 5. Percent soil moisture before and after subsidence at the time of the solution application.

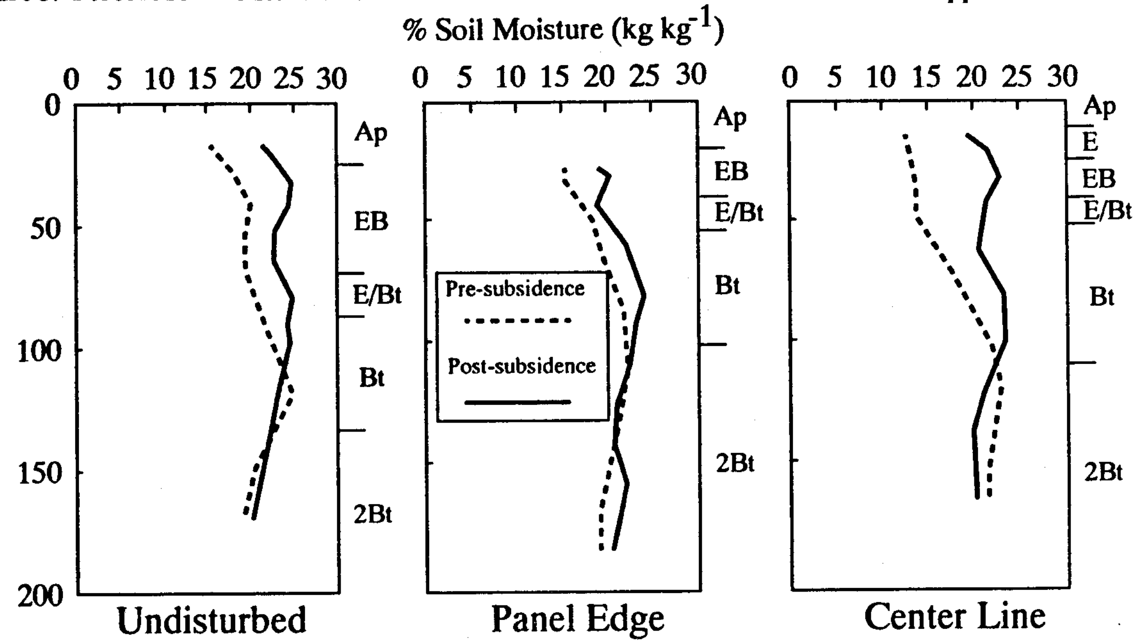
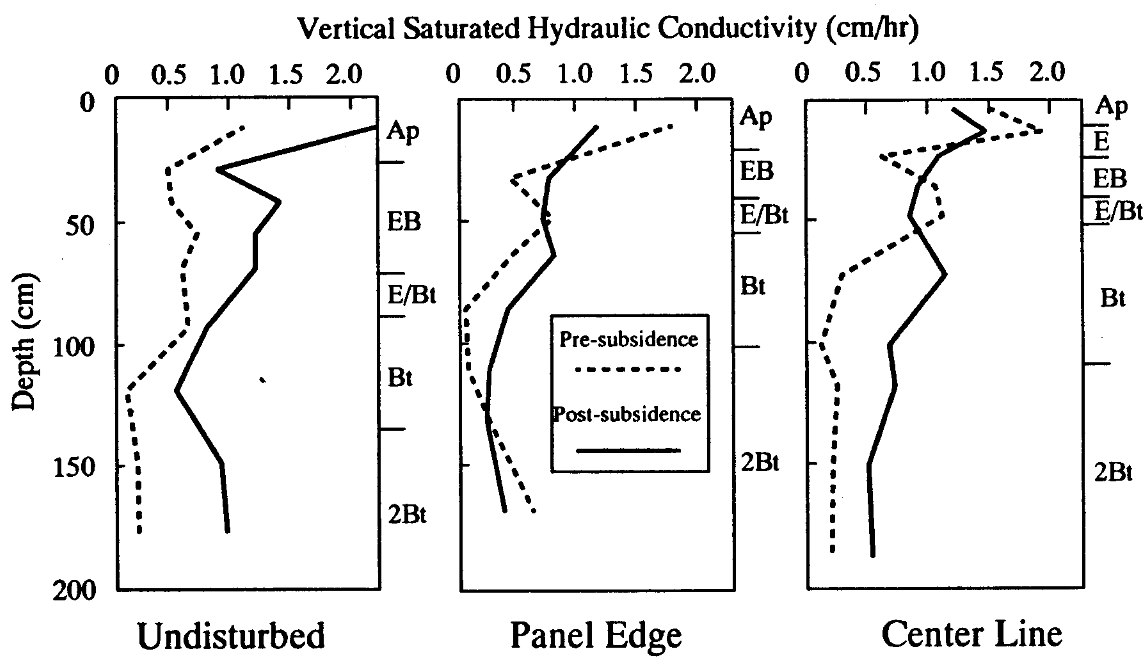


Figure 6. Vertical saturated hydraulic conductivity before and after subsidence. Average of three samples taken from the middle of horizons.



either (1) a high level of variability within the soil horizons; or (2) the method used for determining saturated hydraulic conductivity is unsuitable to detect differences in these soils. However, the fast rate of drainage of the solution tank along the panel edge indicates that an increase in hydraulic conductivity does occur on a larger spatial basis.

Evidence of little differences in dye coverage for the coal panel plots indicates subsidence did not increase total macroporosity throughout the whole soil matrix. Although the total flow paths were not significantly altered, subsidence cracks at the panel edge zone contribute to an increase in preferential flow, as evidence of the dyed cracks and the unusually fast rate of drainage of the solution. This increase in preferential flow along the panel edge could influence the movement of solutes through the solum. One concern is if subsidence occurs over a neglected landfill. The resulting soil fractures could facilitate the movement of contaminates to the groundwater.

The subsidence fractures contribution to bypass flow would be greater with increasing soil moisture (Hoogmoed and Bouma, 1980; Germann et al., 1984; Edwards et al., 1988). Also, soil fractures do not need to extend to the surface for flow to occur in them. Quisenberry and Phillips (1976) showed that preferential flow occurs below a tillage layer where macropores were disrupted. There was a stained large horizontal macropore directly above the E/Bt horizon (Fig. 3a). This indicates resistance to root penetration in this zone and water could flow lateral towards the fractures along active and decayed root channels.

Bromide Movement

Fig. 4 shows Br^- profiles for pre and post subsidence. Bromide values of each sampling depth are averages of 48 samples. All plots showed a steady decline in Br^- levels with depth. Statistical methods using the t-test and a 0.05 confidence level was used to compare Br^- concentrations between horizons of pre- and post-subsidence trails. Statistical analysis revealed that at lower depths, the control plot had significantly greater Br^- concentrations following subsidence. The upper horizons of the control plot had greater or equal concentrations. The panel edge plot had significantly lower levels of Br^- above the Bt horizon after subsidence. Below this depth Br^- levels were greater after subsidence. The center line plot showed similar trends as that of the panel edge plot. Because all plots showed greater Br^- levels after subsidence, a conclusive statement about the relation between transport and subsidence is not possible.

SUMMARY

A field study was undertaken to characterize soil cracks resulting from coal mine induced subsidence and to determine if greater preferential flow of water through soil occurs. A solution of Rhodamine B dye and KBr were applied to characterize changes in soil structure and water movement. Cracks remain in the soil at the mine panel edge eight months after subsidence as revealed by the dye. In addition, the dye solution at this site drained in a much shorter time, compared to the other sites. Dye patterns at the center line revealed no subsidence cracks. A control plot and the two mine panel plots all showed greater bromide concentrations and number of dye stains following subsidence which is believed to be a consequence of greater soil moisture at the time of application. Profiles of percent dye coverage with depth were similar for all plots between pre and post subsidence trails.

Both image analysis of dye stain patterns and the comparisons of Br^- profiles were inconclusive in predicting deeper water flow due to coal mine induced subsidence. However, visual observations and the dye drainage rate show that subsidence cracks along the panel edge zone may increase the possibility for increased preferential flow. This would be the result of flow through the subsidence cracks themselves, not due to changes in macroporosity of the overall soil matrix. The significance of increased preferential flow will depend on soil water conditions. Large scale investigations of surface groundwater quality changes beneath mined panels would aid in determining if subsidence cracks contribute to increased solute movement into the groundwater.

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Lonwall Mine Subsidence of Farmland in Southern Illinois: Near-surface Fracturing and Associated Hydrogeological Effects

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Abstract. The Illinois Mine Subsidence Research Program (IMSRP) coordinated a study to document near-surface fracturing and hydrogeological changes caused by subsidence above an active longwall coal mine in southern Illinois. Using seismic refraction and electrical resistivity, a saturated zone was identified below a depth of 15 ft (4.5 m). There were no widespread subsidence-induced changes to the level or character of this zone. Observations of surface fracturing over the tensile zone of the panel were correlated with strain determinations to estimate a surface strain at incipient cracking of 0.006 to 0.009. Displacement measurements suggested a linear strain profile with depth; therefore, the maximum surface strain and the strain at incipient cracking were used to estimate a maximum depth of surface-fracture penetration of 27 to 31 ft (8-10 m). Resistivity soundings and pseudo-depth profiles over the margins of panel 2 revealed post-subsidence resistivity changes, apparently attributed to fracturing, to an approximate depth of 20 ft (6 m). Resistivity soundings at the centerline of panel 2 revealed major resistivity increases, which are consistent with air-filled fractures extending to a depth of 13 ft (4 m). Repeated soundings after subsidence indicate that these fractures closed to a depth of 3 ft (1 m) about one week after passage of the mine face.

INTRODUCTION

Subsidence associated with high-extraction coal mining causes complex ground displacements and strains that produce tensile fractures at the ground surface. These cracks can alter the hydrologic properties of the soil and bedrock overburden and provide a pathway for contaminant migration into shallow groundwater aquifers.

The advance of the longwall mine face and the development of the subsidence trough on the ground surface is typically revealed by the pattern of open tensile cracks behind the mine face and along the sides of the panel, which is shown schematically in figure 1. Open surface cracks form in the dynamic tensile zone, which follows behind the advancing mine face, and in the static tensile zone along the sides of the panel. Fractures associated with the dynamic subsidence wave are parallel to the mine face in the center of the panel. Near the sides of the panel, however, these cracks turn through a 90 degree arc until they become parallel with the static tension cracks that are aligned with the side of the panel.

Characterization of the distribution, extent, and effects of subsidence-induced fractures is a goal of the Illinois Mine Subsidence Research Program (IMSRP). Therefore, the IMSRP coordinated a study to document ground displacements, fracturing and hydrogeological changes caused by subsidence above an active longwall panel in southern Illinois. This study involved researchers from the Illinois State Geological Survey and Northern Illinois University.

During subsidence, surface displacements were measured within a closely-spaced grid of survey monuments located near the side of the longwall panel. Principal strains were calculated within the grid and correlated with the formation of surface fractures. Inclinometers recorded horizontal displacements and strains as a function of depth; the data were used to estimate the maximum depth of surface-fracture penetration. The electrical resistivity method was used to document near-surface fracturing at different locations over the longwall panel. Pre- and post-subsidence resistivity and seismic refraction profiles were compared to estimate a depth of closure of these surface fractures and document changes in the groundwater table.

SITE

The longwall mine is located in the gently rolling farmland of northwestern Saline County, Illinois, where the local topographic relief is 40 ft (12 m). The mine is producing coal from the 6-ft (1.8 m) thick Herrin Coal at a depth of 400 ft (122 m). Pennsylvanian-age shales and siltstones comprise the bulk of the bedrock overburden (figure 2). Eighty to 90 ft (24 to 27 m) of glacially deposited soils, consisting of loess over clay loam and sandy clay loam with some sand and gravel lenses, overlie the Pennsylvanian-age rocks.

The panel layout is shown in figure 3. Longwall panels 1 and 2 are approximately 2 miles (3.2 km) long, and 668 and 618 ft (204 and 188 m) wide, respectively. The panels are 132 ft (40 m) apart. The mine face of panel 2 advanced to the west at an average rate of 55 ft (17 m) per day during the study.

MONITORING PROGRAM

Deformation Measurements and Observations

A square grid of 16 survey monuments was located to straddle the anticipated zone of maximum-tensile strain near the edge of panel 2 (figure 3) and a transverse line of survey monuments extended across the longwall panel. The location of the tensile zone on panel 2 was predicted from transverse strain measurements of panel 1 (Van Roosendaal et al., 1990). Monuments were spaced 20 ft (6 m) apart (5 percent of the mine depth). Control monuments were placed 320 ft (98 m) south of panel 2. Four inclinometer casings, each 20 ft (6 m) long, were installed in boreholes at the corners of the grid.

Monument positions were surveyed using a Lietz SET 3 total station from a position 180 ft (55 m) south of the panel (figure 3). Prior to each coordinate survey, the position of the instrument station was confirmed by shooting a resection to the control monuments. Baseline

Figure 2. Lithologic column for subsidence research site, Saline County, Illinois.

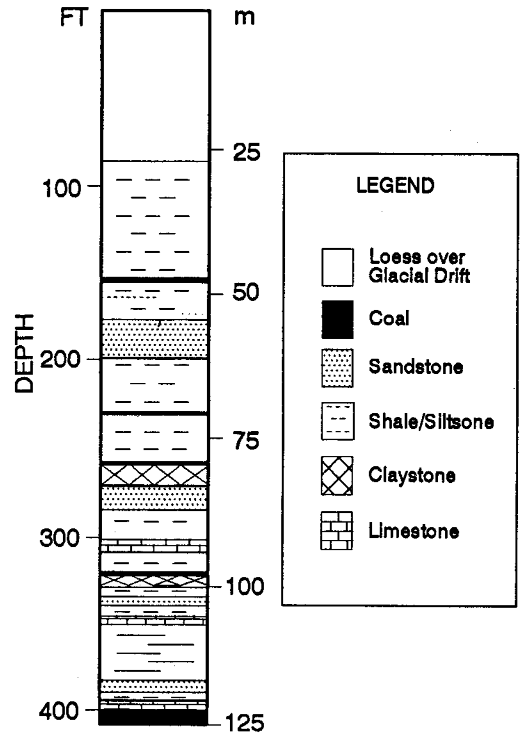
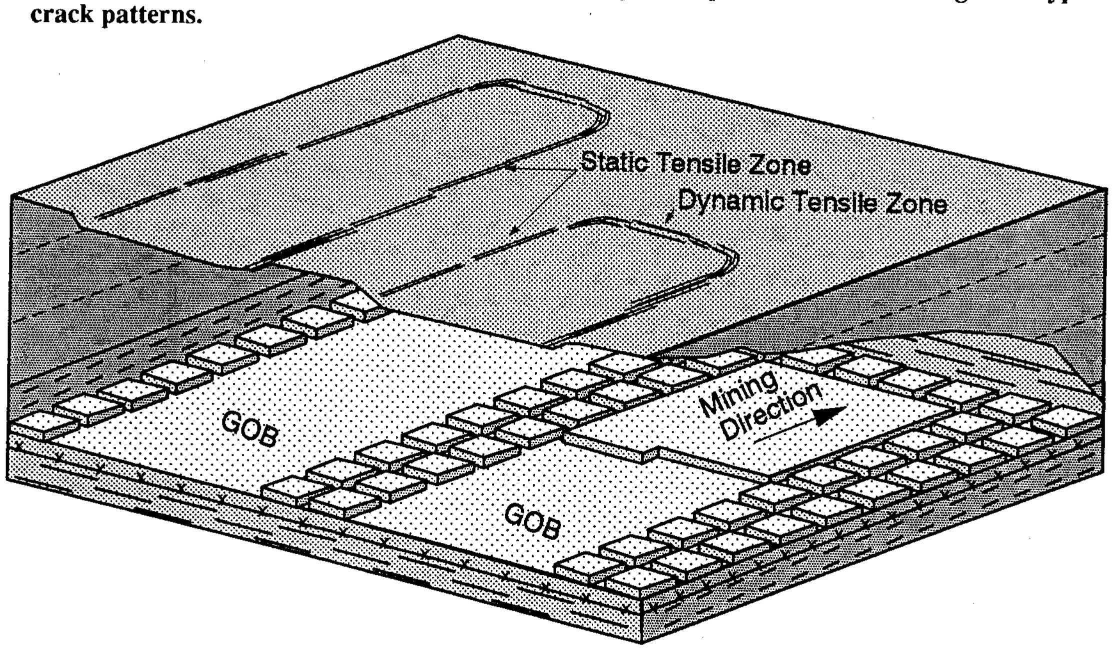


Figure 1. Schematic block diagram of longwall panels showing development of surface trough and typical crack patterns.



surveys of the monuments and instruments were conducted on September 18, 1990. The grid monuments and the tops of the inclinometer casings were surveyed 10 times between September 22 and October 2, 1990, as the longwall face advanced beneath the grid. The seven surveys that best documented the dynamic progression of ground-surface movements were chosen for subsequent data analysis. The positions of the longwall face at the time of these surveys are labeled A through G on figure 3. A final survey (survey H) was conducted two months after the grid was undermined. The transverse monument line was surveyed once during active subsidence (survey C) and again 6 weeks after the line was undermined. The inclinometers were read each time the grid was surveyed.

Electrical Resistivity

Earth resistivity was measured by inserting into the ground 4 stainless steel electrodes in a line, equally spaced, with the outer electrodes carrying the current and the inner electrodes measuring voltage. Earth resistivity was computed from the measured voltage, current, and electrode spacing. With this configuration (Wenner array) the spacing between individual electrodes was expanded to allow current to penetrate deeper into the earth and respond to deeper layers. This procedure is called sounding and the subsurface resistivities were interpreted in terms of a layered resistivity model.

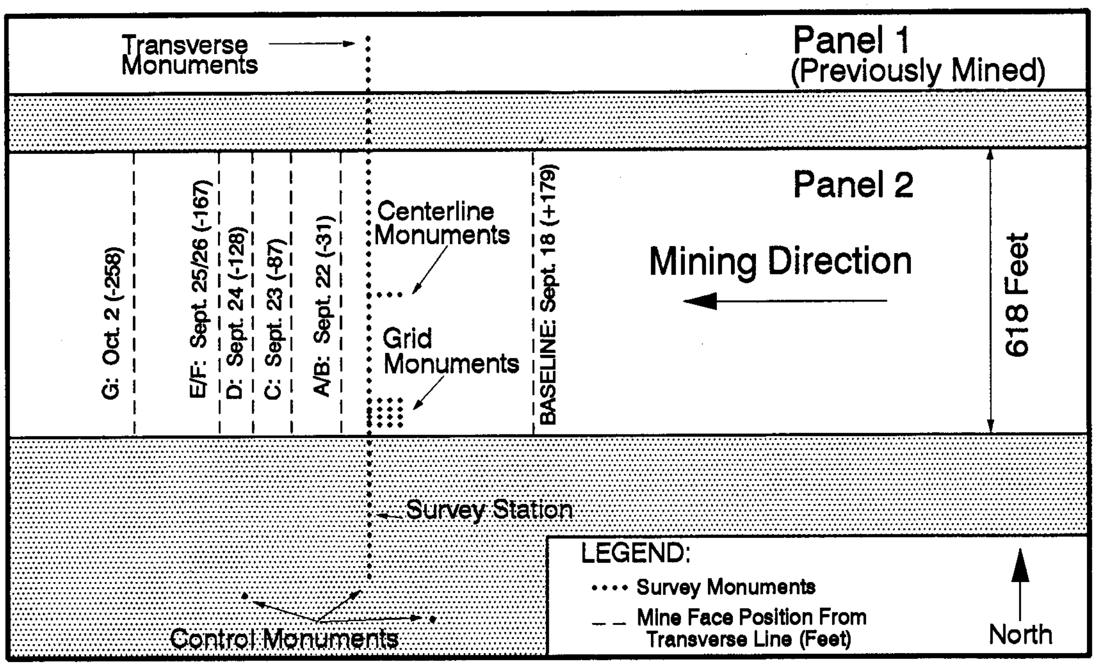
Lateral changes in resistivity were identified by moving Wenner arrays along the earth's surface with a constant electrode spacing (profiling). Soundings were also made at different points along a profile line and a pseudo-depth section was created which, in some ways, resembled a geological cross-section.

As of December, 1991, 25 resistivity soundings have been made over panels 1 and 2, most oriented north-south along the monument line over panel 2. Two north-south pre- and post-subsidence resistivity profiles spanning panel 2 (and parts of panel 1) have also been completed.

Seismic Exploration

Forty seismic refraction lines have been recorded over the center and margins of panels 1 and 2. The seismic refraction method employs a line of motion sensors (geophones) at the earth's surface. At each end of the line a sledgehammer blow on a metal plate sends sound waves into the earth. These sound waves are bent (refracted) by soil and rock layers in the earth and directed back to the surface where they are detected by the geophones. The arrival times of these waves at the geophones are then recorded and interpreted in terms of a layered earth model.

Figure 3. Schematic map of site showing monument locations and longwall mine face position relative to transverse line at times of grid surveys (1 ft = 0.31 m).



RESULTS OF DEFORMATION MEASUREMENTS AND OBSERVATIONS

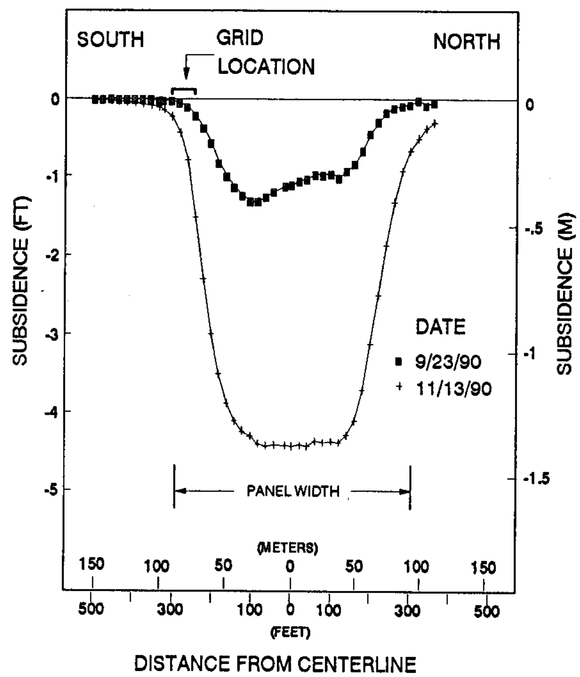
Vertical and Horizontal Displacements

The transverse subsidence profile across panel 2 is displayed in figure 4. The bracket near the south edge marks the location of the grid and the tensile zone. This profile exhibits the flat-bottomed trough typical of supercritical longwall panels (Whittaker and Reddish, 1989). Maximum subsidence was 4.2 ft (1.28 m) after 6 weeks.

The development of subsidence within the grid is shown by a series of three-dimensional surface plots in figure 5. The surface is constructed of vertical-displacement contours with each contour line representing 1 inch (2.54 cm) of subsidence. The 3-D plots are viewed from the northeast.

Figure 6 exhibits the evolution of horizontal displacements of the 16 grid monuments. Initial displacements of the grid monuments were small in magnitude and toward the northeast. As the mine face advanced away from the grid, incremental displacements shifted to the north and northwest and increased in magnitude. The resultant horizontal displacement of the northernmost grid monuments exceeded 15 inches (38 cm). Figure 6 also displays the decrease in the magnitude of displacements between the northern and southern edges of the grid. These displacement gradients cause the tensile strains commonly associated with the tensile zone of the static subsidence profile.

Figure 4. Transverse subsidence profile across panel 2.



Surface Strains and Cracks

The grid was divided into nine square elements with a survey monument located at each corner. Strain analysis followed the "surface element approach" of van der Merwe (1989), which determines principal strains within each element of a grid of surface points. Thus, it was possible to document changes in the direction, magnitude, and sign (tensile or compressive) of the maximum and minimum principal strains on the ground surface and correlate principal strains with observed surface fractures. Using formulae for a three-element rectangular strain rosette (Dally and Riley, 1978, p. 321), the magnitude and direction of the principal strains were calculated for each corner point of the element. Four values were averaged to estimate the magnitude and direction of principal strains within each element.

Principal strains within each element are plotted for surveys A through H in figure 7. Maximum principal strains were all tensile and initially aligned in a northeast-southwest direction (surveys A and B). As the face advanced from east to west and the tensile zone developed, maximum strains increased and rotated to the north. The largest tensile strains (0.027) were measured in the center row of elements in the grid, which confirms that the grid straddles the maximum tensile zone.

The actual open crack patterns recorded within the grid at the times of surveys B, C, E, and H are illustrated in figure 8. These fracture patterns show the progression from the northwest-trending, arcuate cracks of the dynamic wave to the west-northwest trending cracks that eventually developed in the static tension zone as the mine face moved away from the grid.

Subsurface Displacement Profiles

The north-south and east-west profiles of horizontal displacement versus depth for the inclinometer at the northeast corner of the grid are displayed in figure 9. The displacements of the top of each inclinometer were obtained from survey data. These profiles show a linear decrease in horizontal displacement as a function of depth. If the northward displacement profile (transverse to panel) is extrapolated, horizontal displacements reduce to zero at a depth of approximately 40 ft (12 m).

RESULTS OF GEOPHYSICAL METHODS

Stratigraphy from Resistivity Soundings

Resistivity soundings were inverted for a layered geoelectrical model in which layers represent different units observed in a boring made at the center of panel 1

Figure 5. Three-dimensional surface plots showing development of subsidence in the grid. Each contour equals 1 inch (2.54 cm) of vertical displacement. View to southwest.

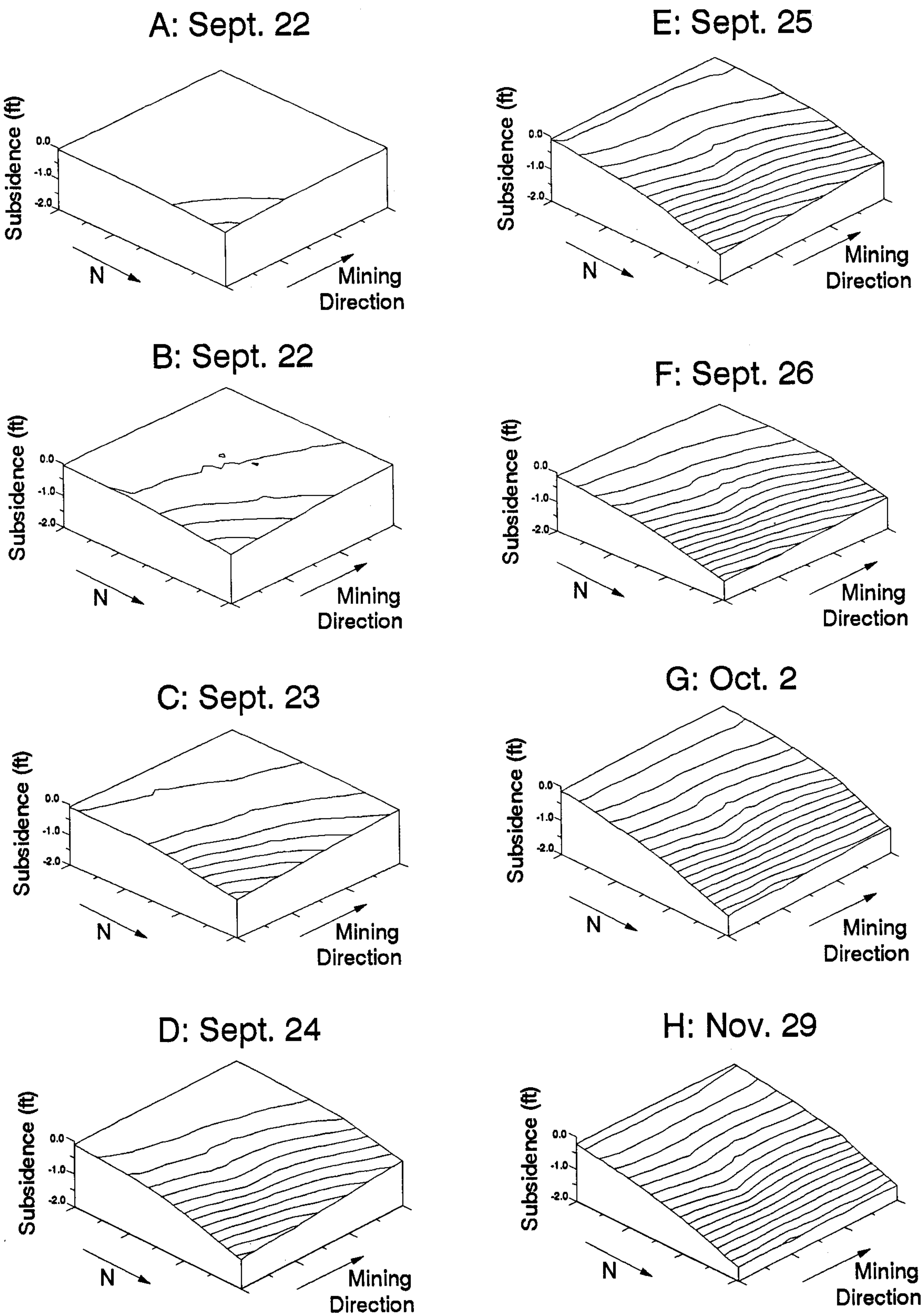


Figure 6. Horizontal displacements of grid and centerline monuments.

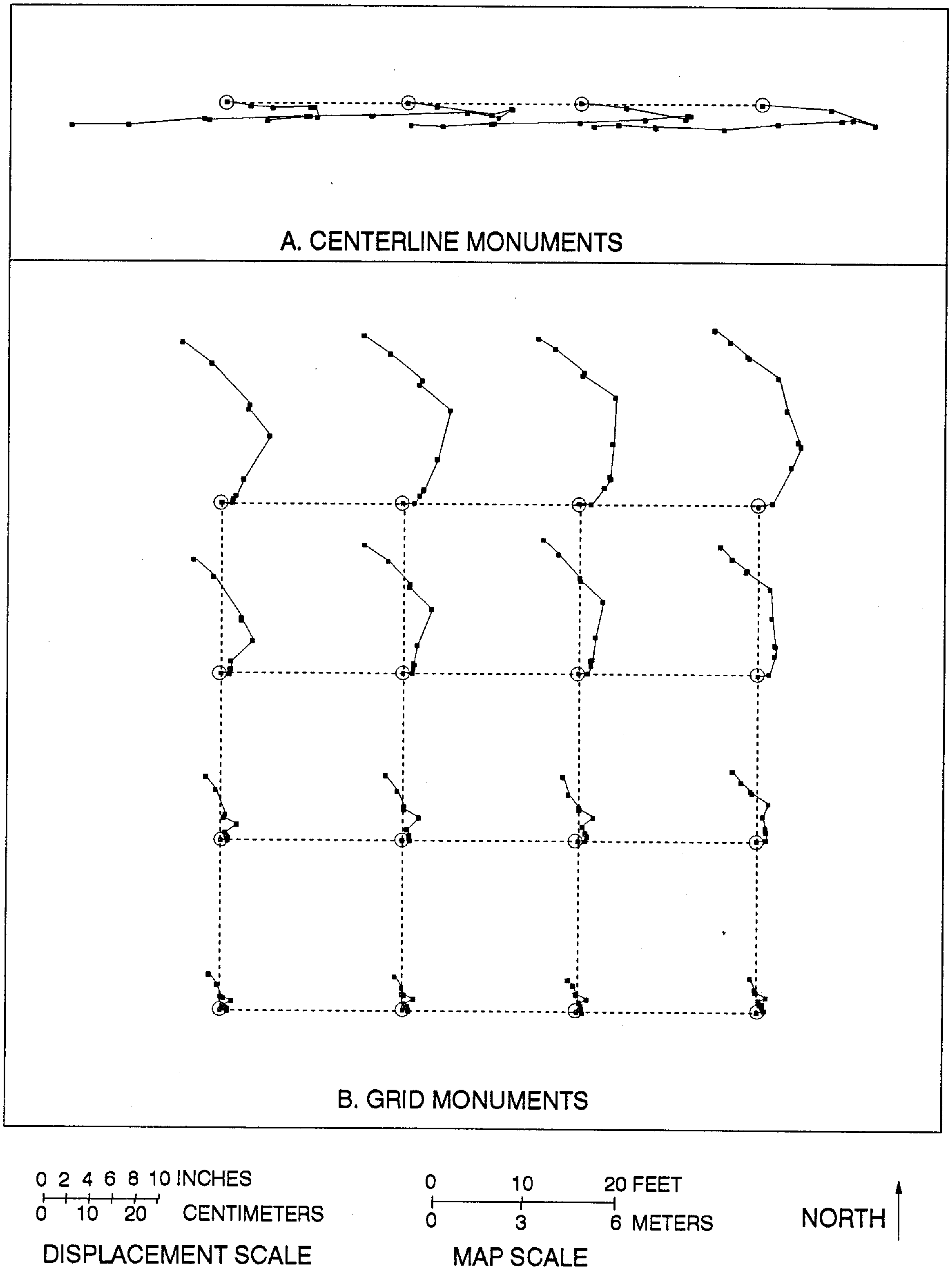


Figure 7. Principal strains calculated within each element. C denotes compressive minimum principal strain.

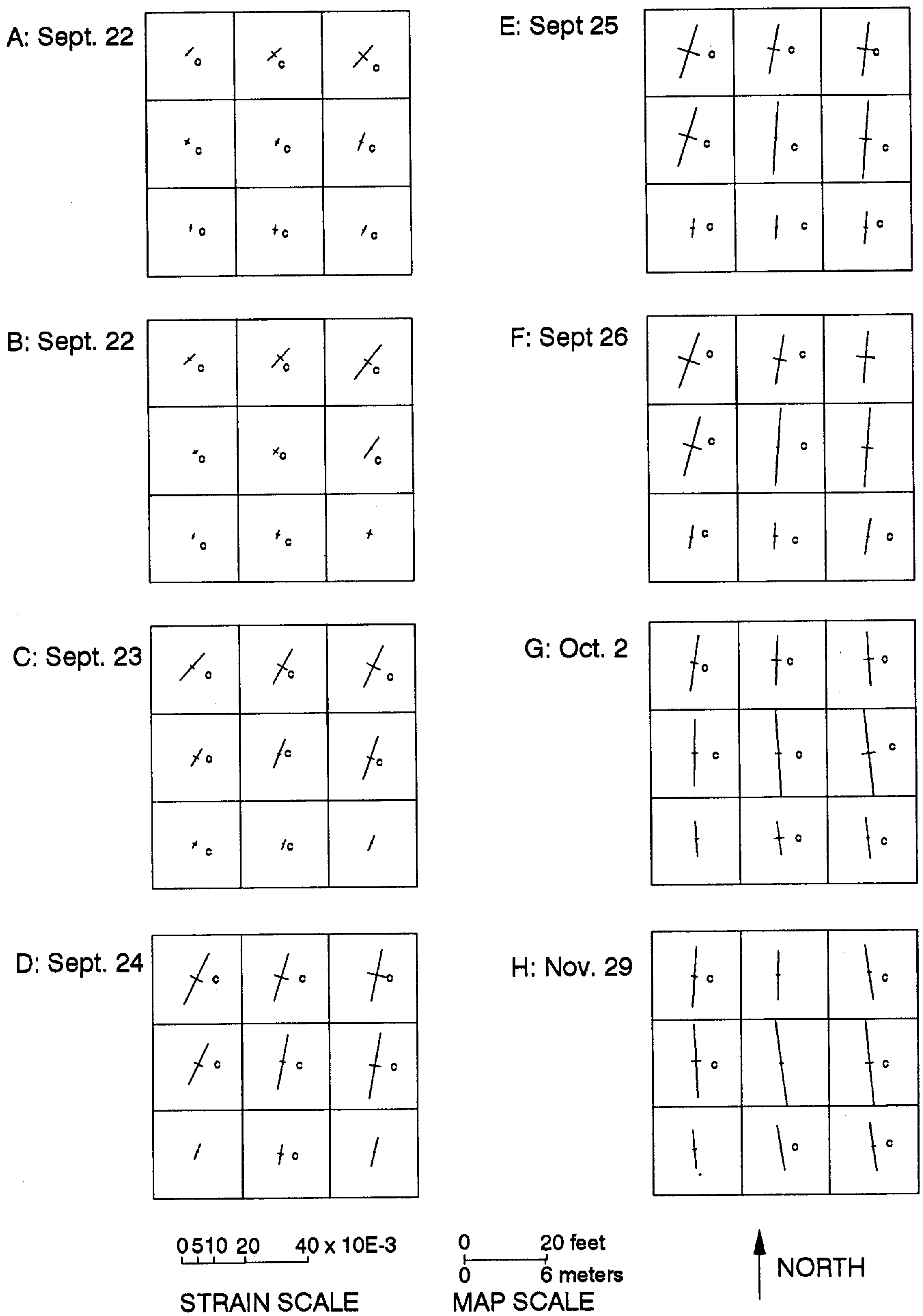
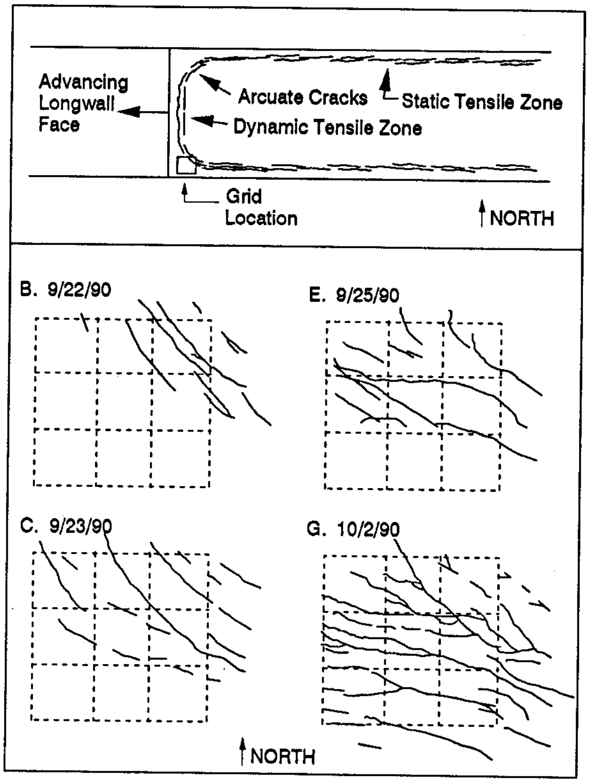


Figure 8. Schematic diagram showing typical pattern of open tension cracks over a longwall panel and the actual crack patterns observed within the grid.



(figure 10). The inversion routine employed the linear filter method to generate model sounding curves for the forward problem and inverted the data using a least-squares algorithm and an equivalence analysis (Interpex, 1988). The geoelectrical layers may be approximately correlated with the boring log as follows: at the surface a 3 ft (1 m) thick, high-resistivity topsoil and loess layer (averaging 75 ohm-m) overlies a 9 ft (2.7 m) thick, clayey, unsaturated layer (46 ohm-m). This lies above a relatively conductive layer (20 ohm-m), which includes saturated clayey and gravelly till overlying bedrock (40-70 ohm-m).

Water-level Fluctuations

A saturated zone at a depth of approximately 15 ft (4.5 m) was identified from seismic refraction surveys made over panel 1 post-subsidence and panel 2 prior to subsidence (figure 11). This saturated zone correlated closely with water levels measured in shallow drift piezometers (Darmody, 1992). Seismic refraction and electrical resistivity soundings over panel 1 (post-subsidence) and panel 2 (pre-, syn- and post-subsidence) show no widespread long-term changes in the level or character of this saturated zone. It is assumed that materials beneath 15 ft (4.5 m) are also saturated.

Figure 9. Horizontal displacement profiles for inclinometer at the northeast corner of the grid.

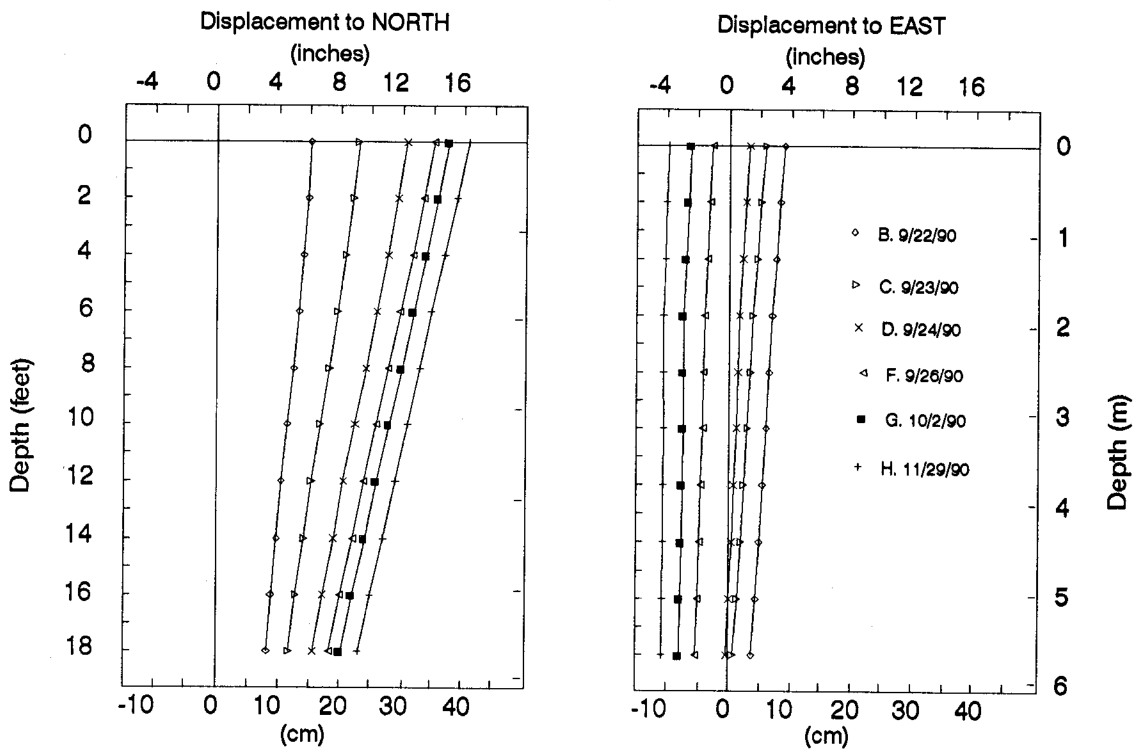


Figure 10. Inverted Wenner array resistivity sounding curve and layered resistivity model with interpreted lithologies (along transverse monument line at north edge of panel 1).

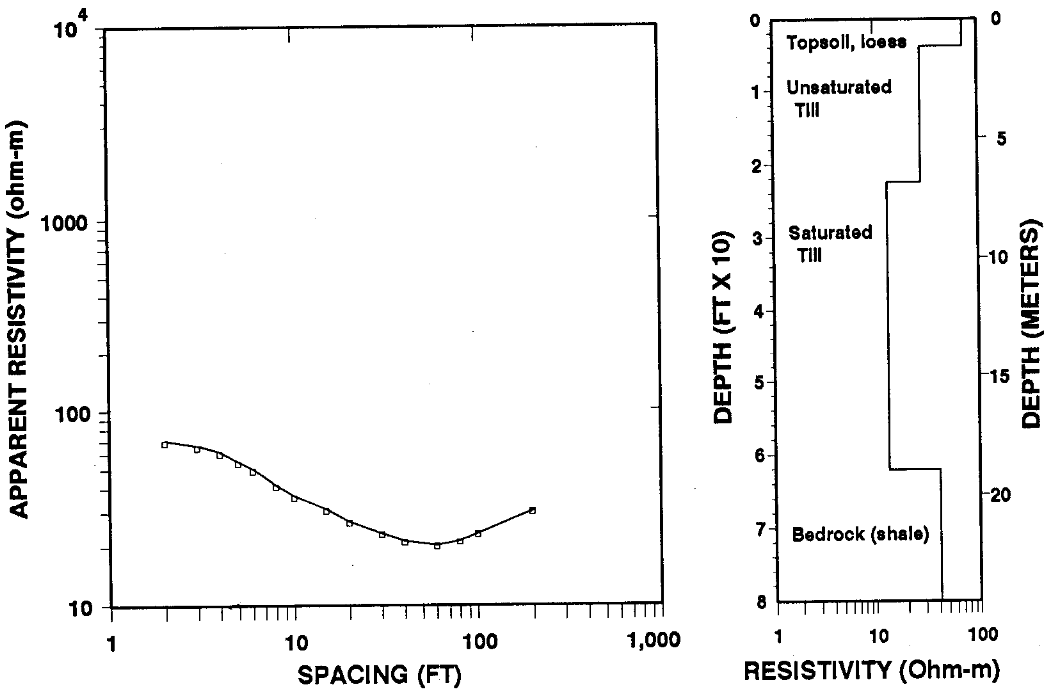
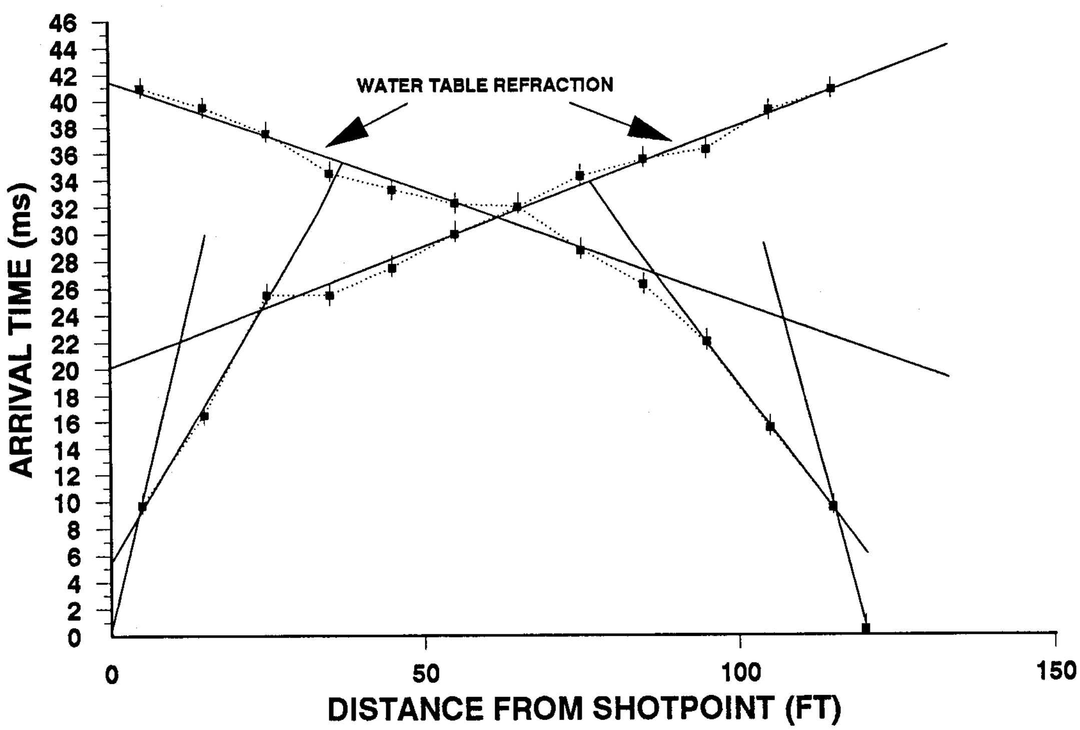


Figure 11. Presubsidence water table seismic refraction travel-time curve from south portion of panel 2. Line segments through data points indicate separate layers. The first layer (topsoil, loess) is about 3 ft (1 m) thick and the water table lies at a depth of 13 ft (4 m).



DISCUSSION: CHARACTERIZATION OF SURFACE FRACTURES

Deformation Measurements

The evolution of surface strain and fracturing reflected the advance of the dynamic subsidence wave through the grid followed by the development of the static tensile zone near the side of the longwall panel. Principal strains were initially directed to the northeast, which was perpendicular to the dynamic wave front. As the dynamic wave passed and the static tensile zone developed, major principal strains rotated to the north and increased in magnitude.

The development of cracks is consistent with the progression of principal strains shown in figure 7. As expected, the orientation of tensile fractures is generally perpendicular to the major principal strain. The initiation of tensile cracks within any given element consistently corresponded to a maximum principal strain within the range of 0.006 to 0.009. This strain at incipient cracking agrees with values published by Kratzsch (1983).

The linear displacement profiles observed with the inclinometers support a neutral-axis bending model for surface subsidence (Kratzsch, 1983). The location of the neutral axis corresponds to the depth at which horizontal displacements reduce to zero. Neutral-axis bending implies a linear strain profile, where strain is a maximum at the surface and decreases to zero at the depth of the neutral axis. The maximum strain at the ground surface (e_{max}) is 0.027 and the estimated depth of the neutral axis is 40 ft (12 m). Assuming that fractures penetrate to a depth where strains are equal to the observed principal strains at incipient cracking (e_i), the depth of penetration is expressed as:

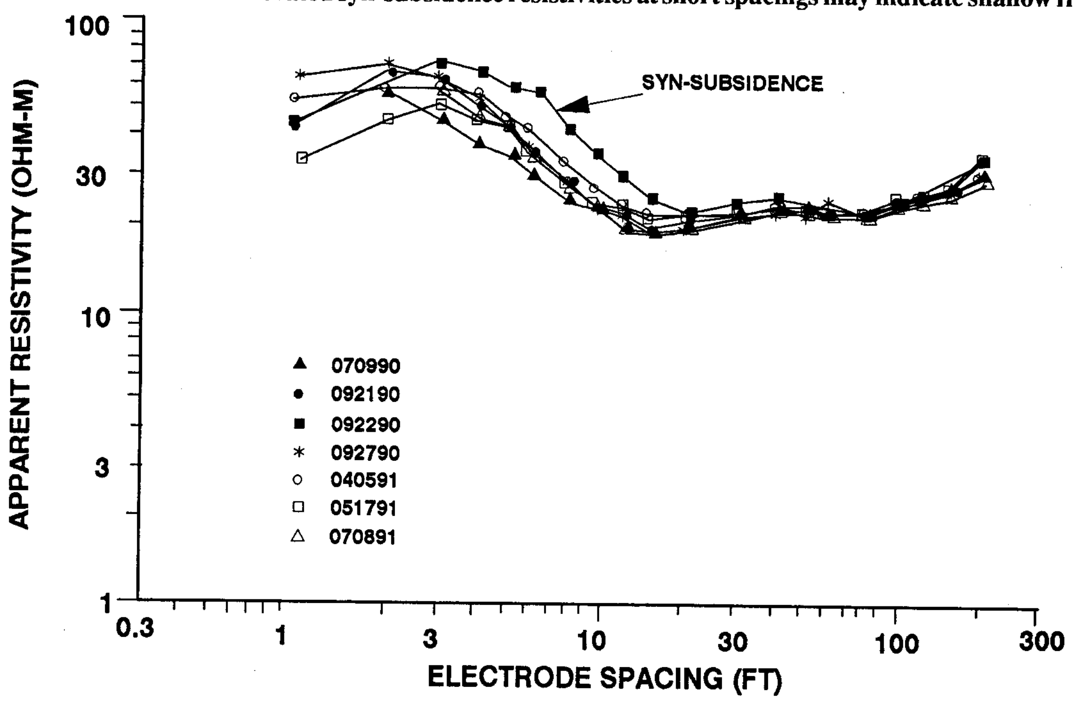
$$D_f = 40 - 40(e_i / e_{max}) \quad \text{[ft]} \quad (1)$$

The observed strains at incipient cracking range from 0.006 to 0.009. Consequently, the maximum depth of surface-fracture penetration ranges from about 27 to 31 ft (8-10m). This simple estimate is based on strains and fractures observed at the surface only, and does not consider the actual stress-strain behavior of the soil or the change in stress with depth.

Bulk Resistivity Changes

Open air-filled fractures in the vadose zone may increase the bulk electrical resistivity of unsaturated tills by providing barriers to electrical current flow (Taylor and Fleming, 1988; Carpenter et al., 1990). Increases in fracturing in the glacial materials overlying bedrock were identified through the use of resistivity soundings. Soundings made at the centerline of panel 2 exhibited major resistivity increases at short spacings, which are probably due to air-filled fractures in glacial deposits above the saturated zone (figure 12). The observed resistivities are consistent with fractures ex-

Figure 12. Multiple Wenner array resistivity soundings over the center of panel 2 before, during and after subsidence. Elevated syn-subsidence resistivities at short spacings may indicate shallow fracturing.



tending to a depth of at least 13 ft (4 m). If this interpretation is correct, these fractures may provide pathways to the water table for chemicals used in surface agricultural activities. However, repeated soundings suggest the deeper portion of these fractures have closed up within about 1 week of passage of the mine face; shallow fractures (3 ft [1 m] deep) may have remained open up to 9 months after subsidence.

Resistivity Profiles

Pseudo-depth sections are constructed by plotting apparent resistivity at different stations as a function of electrode spacings. The section is only a general guide to resistivity changes along the profile. While larger spacings are influenced by deeper structure, the conversion between depth and spacing is nonlinear (in places a 40 ft [12 m] spacing equates roughly to structure at 15-20 ft [4.5-6 m] depth). Wenner array resistivity soundings were made every 20 ft (6 m) to construct a pseudo-depth section along the profile line. Profiles made across panel 2 one month after subsidence (figure 13) showed increased resistivity along the margins of the panel, possibly reflecting air-filled fractures in the upper unsaturated zone. Resistivity decreases, however, extended below this along both margins of panel 2 and over the north barrier pillar between panels 1 and 2. Moisture percolating downward along fractures in this interval of the drift to a depth of about 13-20 ft (4-6 m) may have led to the resistivity decreases.

CONCLUSIONS

1. Using seismic refraction and electrical resistivity, a saturated zone was identified below a depth of 15 ft (4.5 m). There were no widespread subsidence-induced changes to the level or character of this zone.
2. Deformation measurements and resistivity soundings both predicted a shallow depth of closure (20 to 30 ft [6-9 m]) for subsidence-induced surface fractures. Subsurface profiles of horizontal displacement versus depth, principal-strain determinations and observations of surface fractures within a monument grid, were used to estimate a maximum penetration depth for surface fractures of 27 to 31 ft (8-10 m) over the maximum tensile zone on the southern edge of panel 2. Resistivity soundings and pseudo-depth profiles over the margins of panel 2 revealed post-subsidence resistivity changes, apparently attributed to fracturing, extending to an approximate depth of 20 ft (6 m).
3. Resistivity soundings at the centerline of panel 2 revealed major resistivity increases, which are consistent with air-filled fractures extending to a depth of 13 ft (4 m). Repeated soundings after subsidence indicate that these fractures closed to a depth of 3 ft (1 m) about one week after passage of the mine face.

ACKNOWLEDGMENTS

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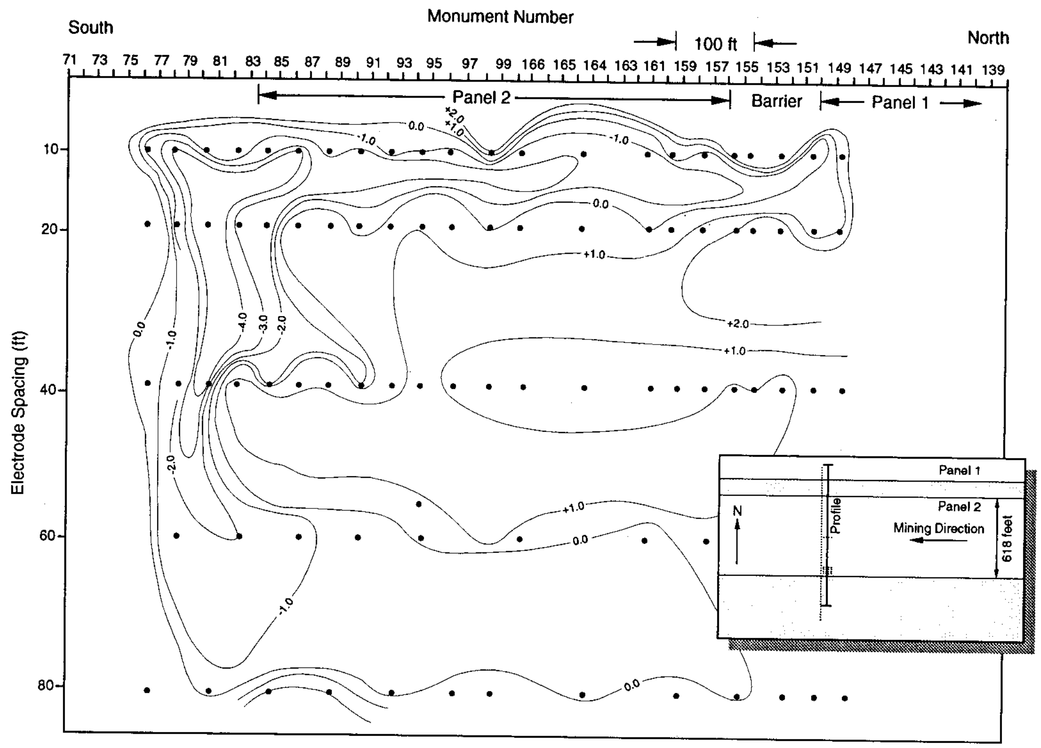
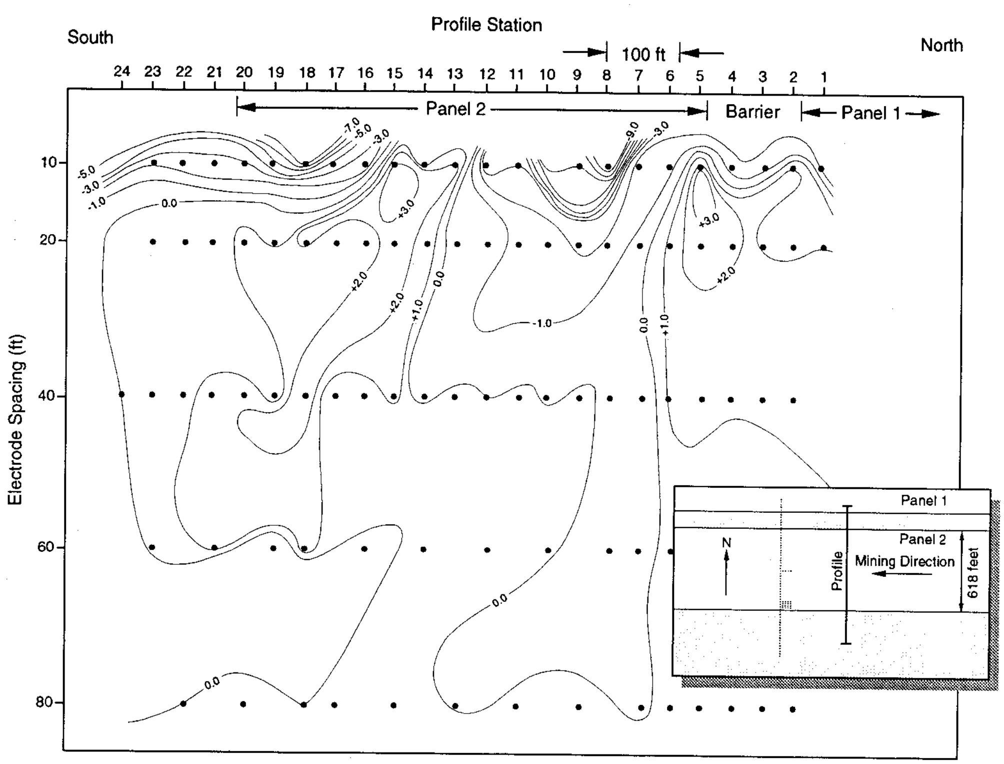
Figure 13. Pseudo-depth sections depicting pre - postsubsidence apparent resistivity differences across panel 2 (contoured in ohm-m).





Implementation of the Agricultural Lands Productivity Formula: Practical Application

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Abstract. Under the Surface Mining Control and Reclamation Act of 1977, the mining industry was required to replace prime farmland to its pre-mining level of productivity. In Illinois, the Illinois Department of Agriculture was charged with the responsibility of developing a method of assessing the productivity capability of reclaimed mined land. The Agricultural Lands Productivity Formula was adopted in 1986, but not without considerable effort being given to the development of a carefully detailed sampling. The implementation of this program required developing field sampling procedures, assessing manpower requirements, providing intensive training and office support for sample enumerators, and integrating two federal agencies into the program.

INTRODUCTION

Illinois coal falls within the sequence of rocks commonly called the Pennsylvanian System which was developed 280 to 315 million years ago. These coal bearing rocks underlie 65% of the 56,400 square miles of Illinois and contain a coal resource of approximately 181 billion tons (Treworgy and Bargh, 1982). These figures made by the Illinois State Geological Survey are an estimate of total coal in the ground, much of which is not recoverable under present economics or present engineering technology.

LEGISLATIVE HISTORY

On August 3, 1977, President Carter signed into law the "Surface Mining Control and Reclamation Act", Public Law 95-87. This Federal Act required most states to pass legislation that would comply with the federal statutes in order to receive primacy for enforcement of the federal law.

In 1979, Illinois passed Public Act 81-1015, "The Surface Coal Mining Land Conservation and Reclamation Act," which enabled Illinois to develop, submit for approval, and receive conditional approval of the Permanent Program on June 1, 1982. With that approval, Illinois received primacy under the Federal Act for regulation of the coal mining industry.

LITERATURE REVIEW

The Federal Act in Sections 510(d)(1), 515(b)(19), and 519(c)(2) and the Federal Rules and Regulations (Federal Register 1979) concerned with reclamation of mined prime farmland indicate that success in revegetation shall be determined on the basis of crop production from mined areas compared to that of approved reference areas or other technical guidance procedures. State Rules and Regulations in Section 1785.17e(3), 1816.116a(3)c, 1817.116a(3)c, and 1823.15b(2) (62 Illinois Administrative Code) requiring proof of soil productivity has led to the initiation of considerable research to determine and evaluate methods of reclaiming mined prime farmland.

Hoffman et al. (1981) studied both vegetative production and animal performance on mined land and obtained results similar to those from undisturbed soil. However, Nielsen and Miller (1980) reported that corn yields on mined soil were 4 to 90 percent less than adjacent native soils, depending upon topsoil applications and age. Grandt (1978) found that corn yields decreased over a 3-year period when corn was grown on a graded spoil, but yields were relatively constant where topsoil had been replaced. Most of the published research has addressed the methodology of reclaiming mined soils for crop productivity, with research results often reflected in rules and regulations concerning mined land reclamation.

A major difficulty in predicting crop yield at either a reclaimed or unmined site is the variability in weather and its effects on crop yield. Considerable research has been conducted evaluating relationships between crop yield and weather variables (Runge and Odell, 1958; Runge, 1968; and Thompson, 1975), and crop yields, weather variables, and soil parameters (Robbins and Domingo, 1953; Leeper, et al., 1974; and Nelson and McCracken, 1962). However, applications of specific parameters in this research to individual sites for purposes of calculating a yield standard would not be appropriate since agronomic management factors are likely to be different from those used in the cited studies. For example, recommended crop varieties, plant populations, herbicides and fertilizer rates change over time and these factors would affect crop yield based on current management practices. Variable weather conditions affect crop productivity as well as affecting parameters used to predict crop yield. Thus, yield equations developed from research data would have limited value in predicting individual site yields.

The Federal Act (PL 95-87) required that prime farmland must be reclaimed to equivalent or higher yield levels compared to non-mined prime farmland in the surrounding area (Jansen, 1981). Researchers indicate that reconstruction of mine soils is site specific (Schuman and Power, 1981) and, thus, productivity comparisons therefore might be expected to be site specific. This would minimize differences in yields that might be attributed to factors other than those studied.

It is apparent that the research methodology for evaluation of the productivity of reconstructed soil is to make comparisons with unmined adjacent soil at specific sites. Federal and State rules and regulations suggest similar methodology or other technical guidance procedures. The methodology proposed in the Agricultural Lands Productivity Formula (ALPF) developed by the Illinois Department of Agriculture (IDOA) evidently would be categorized as "other technical guidance procedures" as the number of sites to be evaluated and the limited resources available for site evaluation make it prohibitive to use the research approach for evaluation of reconstructed soil productivity at each site. Therefore, the purpose of the Agricultural Lands Productivity Formula is to provide a calculated standard yield to be used for comparison to determine if productivity has been restored to mined land.

The Agricultural Lands Productivity Formula (ALPF) has advantages as a method for determining a yield standard. Calculating a yield standard is much less expensive than managing a comparable research plot on undisturbed soil, and it also provides for seasonal adjustment in the yield standard based on the use of the USDA Agricultural Statistics Service county estimated average yield per acre. The ALPF also utilizes the computation of estimated soil productivity at a high level of management (Fehrenbacher et al., 1978) as well as the "average" management of crops reflected by the county yield that is reported.

The calculated yield standard produced by the Agricultural Lands Productivity Formula (ALPF) is not site specific, the importance of which was emphasized by Schuman and Power (1981). Variations in weather during the growing season such as drought, rain, or hail storms can be site specific and quite detrimental to site yield even though the county average is not greatly affected. It appears that some adjustment in yield at a specific site may be necessary when "abnormal" weather occurs at specific sites within a county.

Little or no research has been published that provides suitable methodology or parameters for predicting yields from constructed soils or even unmined soils at a specific site at some future point in time. As has been suggested previously, agronomic management factors change over time and published research showing yield prediction equations are generally not suitable beyond the conditions specific in the research.

Computations in the Agricultural Lands Productivity Formula integrate both county weather and management practices during a given year, as well as the use of expected high management yields (Fehrenbacher et al., 1978) by soil type to reflect recognized productivity differences in soils. Thus, it might be concluded that the yield standard calculated by the Department of Agriculture's productivity formula is more current relative to weather and county management practices than some alternative choices (i.e., published yield equations, published farm yields, etc.).

LOSS ADJUSTMENT

The problem of major weather disasters at a given site relative to a standard yield will need adjustment. For example, corn is relatively sensitive to moisture stress at flowering (Denmead and Shaw, 1963; Robbins and Domingo, 1953) and differences in moisture stress at flowering may result in relatively large differences in yield at harvest. It is entirely possible that one part of a county can be severely deficient in moisture while the remainder of the county has a relatively normal growing season. A provision has been made to make adjustments for "largely abnormal" growing conditions at a test site where yields are to be compared against a county-wide standard. An abnormal growing condition might include drought, flood, hail, etc.

Crop adjusters certified to perform adjustments by the Federal Crop Insurance Corporation (FCIC) are utilized on a site specific basis to evaluate reported crop losses. FCIC adjusters are provided with field delineation maps by the Illinois Department of Agriculture (IDOA) and are assigned, on an as requested basis, to perform loss adjustments. Due to the lack of historical crop data, it is necessary to perform crop appraisals during the growing season. Loss adjustments requested by industry are determined by a comparison to the appraisals previously made. The use of loss adjusters is optional because it is an added cost that must be born by industry. The IDOA program allows for the mining company to cancel requested appraisals any time during the crop season. Cancellation may be appropriate should the site specific instance of loss not materialize.

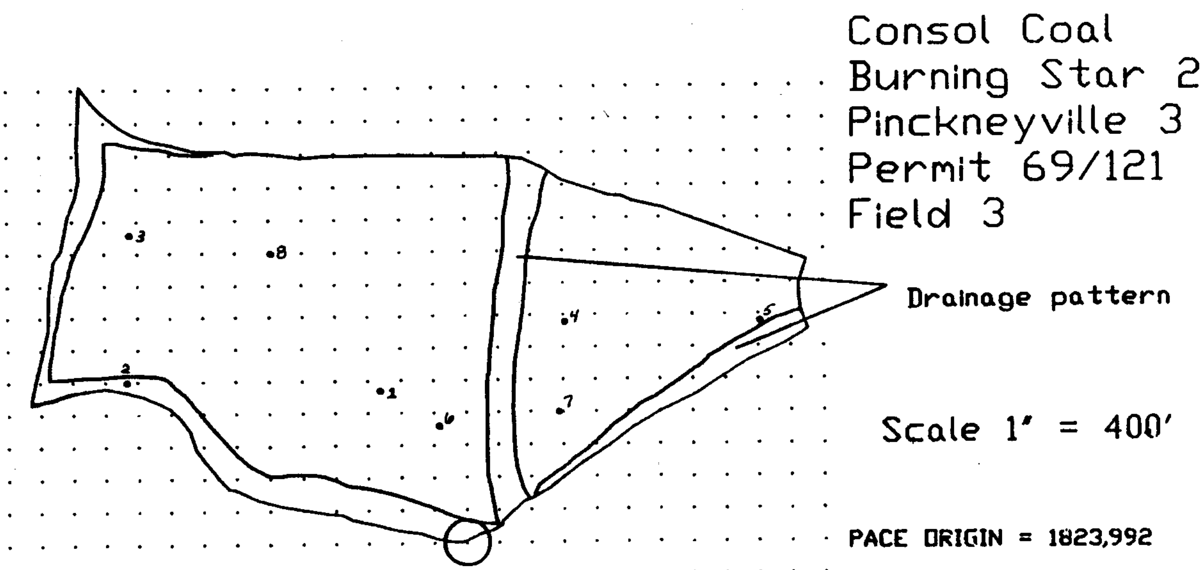
SAMPLING

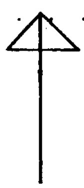
An important section of the productivity formula is the sampling procedure, and an integral part of that is the location of the sample points. The Department looked at many procedures used by various groups or agencies involved in field sampling. Everything considered was based on statistical sampling procedures that involved only partial field representation. Due to the very nature of the reconstructed soils, we could assume there was no homogeneity in the soils that would lead to consistent crop production.

In an effort to account for the variability that we encountered, it was decided to impose a whole field sampling procedure, using complete randomization of sample points. A customized computer program was created by a private contractor to generate random samples points by computer. Once sampling points are generated, the program creates a script file which works interactively in the Auto-Cad computer aided drafting environment. The final product is a single sheet of paper with field boundaries delineated and all sampling points located from a single point of origin by pace count (see attached Figure 1). The use of this sheet makes it simple for the field enumerator to locate and take samples. Although the coefficient of variation remains high for the individual sample points, the correlation of the mean to the actual harvest remains within five percent. Provisions were also made in the Illinois rules that in every case a certified whole field weight would take precedent over sample weights.

In preparing to implement the formula, a number of crop sampling procedures that could be adapted to our needs were reviewed. Ultimately, the procedures of the USDA Agricultural Statistics Service were chosen to be incorporated in to the Productivity Formula. USDA hand sampling procedures have evolved over many decades of actual field sampling and have proved to be

Figure 1. Illinois Department of Agriculture sample enumerator field sheet.





Summary of Random Points Generated for .dxf

pace origin is (1823,992)

1	Paces:	-105 W,	187 N	feet:	263 W,	468 N
2	Paces:	-413 W,	199 N	feet:	1033 W,	498 N
3	Paces:	-409 W,	383 N	feet:	1023 W,	958 N
4	Paces:	123 E,	271 N	feet:	307 E,	678 N
5	Paces:	363 E,	271 N	feet:	907 E,	678 N
6	Paces:	-33 W,	143 N	feet:	83 W,	358 N
7	Paces:	115 E,	159 N	feet:	287 E,	398 N
8	Paces:	-237 W,	359 N	feet:	593 W,	898 N

the most reliable. The only exception to USDA procedures was for hay. There was no hand sampling procedure developed for hay which would meet our needs. The IDOA began a long literature search which resulted in the adaptation of a formula provided to us by Fenn & Company of Cottage Grove, Oregon.

A major problem of hand sampling hay is its rapid decomposition after it is cut. Annual tonnage figures for hay, produced by the Agricultural Statistics Service, and used almost universally are in dry matter content. Within an hour after sampling, decomposition of the mixed hay substantially alters the dry matter content. The number of samples to be taken in a day and their total volume made transportation to a lab for moisture content determination impractical.

An extensive review of available field moisture meters was undertaken, only to determine that the variability of readings made reliability unacceptable for our purposes. The company which was ultimately chosen (Dickey-John Corp), worked directly with the Illinois Department of Agriculture to improve useability of the meter of choice. The Agency undertook an intensive sampling program whereby we provided carefully sealed and iced samples which were laboratory tested and correlated for the specific machines.

Feeling that the field moisture problem had been overcome, field sample correlations were begun only to find that field scales were not sufficiently accurate. We needed accuracy within one tenth of a pound or greater. This involved the purchase of some very expensive platform scales which were difficult to transport and set up. When all was said and done, a very accurate hay plot sampling method determining dry matter tonnage in the field had been developed. When the first requests for hay sampling came in, logistics and volume made the initial field sampling plan unworkable. It was quicker, cheaper and more responsive to industry needs to simply weigh a representative sample of bales. Using bales for weights still required moisture testing, which introduced still another round of problems with taking moisture samples. The decision was made to displace the variability in countering the inherent problem with determining field moisture content with any degree of accuracy. In developing yield calculations, an administrative decision was made to establish a 15% moisture standard to replace the dry matter standard. All dry matter calculations are adjusted to 15% moisture, thus eliminating the variability problems of the sampling equipment.

In developing the appropriate sampling technique, a few rough edges had to be smoothed out. One such problem was the exact location of the sample in relation to the last pace count. In the process of sampling wheat, it was observed that enumerators had a tendency to lay the sample frame down and push it up against the closest wheat row. This would increase the yield by one row which generally was about 33 per cent. The enumerator had to make sure that the sample frame laid perpendicular to the toe of his/her shoe on the last pace count.

Another problem had to do with thin or bare spots in a field. As an enumerator proceeds ahead with the pace count, he/she may observe a thin or bare spot in the field. When approaching this spot, the brain automatically adjusted the length of their pace to either end short of the bare area or pass over it. This is easily compensated for by having the enumerator stop the pace count short by 5 paces and measuring the remaining distance with a tape measure.

MANPOWER

Implementing a new program posed a challenge with regard to budgeting for the correct number of man-hours to collect and process field samples. The Department of Agriculture was able to start with some basic values that were obtained in early field trials. Approximately 20 minutes were allocated per sample for collection with up to another 15 minutes allowed for paperwork and preparation for mailing the samples. Once the samples are received in the lab for moisture testing, another 30 to 40 minutes can be added per sample for processing. A starting figure of approximately 1 to 1.25 hours per sample may be used for cost estimates for grain sampling. In addition to the man-hours involved, a postage fee should be assessed for mailing to a laboratory facility (see Table 1 for sample densities).

The cost of sampling baled hay becomes more difficult to estimate because of multiple cuttings, different bale sizes, and whether the bales are stacked or left in the field. For the first year, it would be safer to appraise the cost of field sampling baled hay by projecting the cost as if the hand sampling method was being used. If this procedure is used, remember to reduce the single sample time value by the estimated lab time, as hay samples would not be processed in a lab. Hay samples used for calculation purposes would also reflect the total number of cuttings for a season.

CONCLUSION

The Illinois Department of Agriculture spent several years developing and implementing the Agricultural Lands Productivity Formula. This method of reclamation productivity assessment has allowed Illinois to proceed with the release of bond on prime farmland while satisfying the agricultural and environmental interests. The industry has shared our problems and has been understanding as we matured into a fully functioning program. Now, working together, we can be assured that the agricultural resources of Illinois will remain for future generations.

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Table 1. Illinois agricultual lands productivity formula.

Size of Bond Release Field	Minimum Number Of Samples
COR N	
4 - 39 acres	10
40 - 279 acres	14
280 - 639 acres	18
640 acres or more	30
SOYBEANS	
Size of Bond Release Field	Minimum Number Of Samples
4 - 39 acres	10
40 - 279 acres	12
280 - 639 acres	16
640 acres or more	26
WHEAT - OATS	
Size of Bond Release Field	Minimum Number Of Samples
4 - 39 acres	6
40 - 279 acres	8
280 - 639 acres	10
640 acres or more	14
SORGHUM	
Size of Bond Release Field	Minimum Number Of Samples
4 - 39 acres	10
40 - 279 acres	16
280 - 639 acres	28
640 acres or more	40
MIXED HAY	
Size of Bond Release Field	Minimum Number Of Samples
4 - 39 acres	5
40 - 279 acres	10
280 - 639 acres	20
640 acres or more	(1) additional per 35 acres

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Cropland and Hayland Productivity Restoration on Mined Land in Illinois

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Abstract. The Surface Mining Control and Reclamation Act (PL 95-87) introduced many new controls on the coal industry. One of these was the requirement to re-establish cropland and hayland productivity. Each state has been required to establish measuring techniques for evaluating productivity restoration. In 1986 the Agricultural Land Productivity Formula (ALPF) became an approved regulation to assess productivity restoration on both cropland and hayland in Illinois. Since that time several hundred field-years have been tested at 23 mines around the state. Initial results indicate that wheat and hay crops have been tested the most. Wheat crops have met or exceeded the required target yields a greater percentage of the time than soybeans, corn or hay. These results are attributed to the poor physical conditions (compaction) at the time of testing and its effect on the individual crops. Compaction alleviation (deep tillage) is having positive results relative to those fields that have not been augmented.

INTRODUCTION

Cropland reclamation does not have a long history in the art of reclamation. Illinois created its first cropland reclamation standard with the passage of the Surface-Mined Land Conservation and Reclamation Act of 1971. This regulation, commonly known as Rule 1104, established a rooting medium quality with defined limits of clay, rock size and quantity. Major changes were added in 1976 to include topsoil replacement and further limit the rock content. Rule 1104 includes all soils capable of producing crops which is a broader definition than prime farmland soils. In 1977, with the passage of the Surface Mining Control and Reclamation Act, specific provisions for prime farmland restoration and actual measurements of restored cropland productivity became effective. Illinois also retained its Rule 1104, which is now known as high capability land.

It is virtually impossible to operate a large or medium size surface or underground mine in Illinois without affecting prime farmland or high capability land (1). This results in a significant acreage of land, primarily from surface mines, being returned to a post mining land use of cropland. The concept of the productivity regulations is to measure the yields of the reclaimed fields to either 90% or 100% of their premining yields.

The regulations allow this to be done by determining a soils premining yield potential and comparing it to a reference area or to established values in the literature. Adjustments are made for seasonal weather influences. Numerous problems were anticipated in Illinois for reference areas near the mine site. These included finding representative sites and equivalent management monitoring. In 1986, Illinois promulgated its measurement technique called the Agricultural Land Productivity Formula (ALPF)(2). This technique is a blend of both methods. The basic concept is direct comparison of the yield potential of the soils in the permit with the yield potential of the soils that are cropped in the county. Each year the changes in county average yields proportionately alter the required yield targets for the permit area for corn, wheat, soybeans and hay.

MATERIALS AND METHODS

Under the ALPF operators must submit requests for field testing. Requests must include the crop to be grown and maps of the fields. The current crops which are approved for use are corn, soybeans, wheat and hay. All cropland must have one successful year of corn and is limited to one successful year of hay or wheat. During the harvest season random samples are taken to determine if the field meets or exceeds the success standards.

A statistical comparison, one-sided t test with 90% confidence, is used to compare the sample yields with the target yields established for that year. Current regulations set a 90% and 100% of target standard for high capability and prime farmland, respectively. A total of 646 field sample success results from 1985 through 1990 were compiled from 23 mines and evaluated for the differences between crops, the effects of subsoil replacement technology and deep tillage (>18 inches). Subsoil replacement has been placed into four categories which include: bucket wheel excavator (BWE); truck shovel (TS); scraper, which includes combinations with trucks (S); and direct cast by dragline (D). The deep tillage technology includes the TLG 12 vibrating ripper, the DMI static shank plow, the slip plow, Jones vibrating ripper and Sahara static ripper. For the purpose of this paper, only information on interactions between tillage, crops and soil replacement methods with at least 5 individual field-year tests will be interpreted.

RESULTS AND DISCUSSION

Of the 646 field-years of crop productivity tested under ALPF, approximately 200 field-years of each corn, hay, and wheat have been tested; 48 field-years of soybeans have also been tested for productivity. Scraper replaced rooting media has been the most commonly tested (326 field-years), followed by bucket wheel excavator (215 field-years), dragline (77 field-years) and truck shovel (28 field-years). Two hundred field-years of the 646 tested have been deep tilled to greater than 18 inches; 446 field-years have not been augmented. When looking at individual crops independent of soil replacement technology or deep tillage, the data compiled indicated that wheat was the most successful crop in meeting the requirements of ALPF (Figure 1).

Seventy (70) percent of the wheat field-year tested met production requirements, followed by soybeans (62.5%), corn (59%) and hay (48%). Presumably, any poor soil physical conditions after reclamation (compaction) would affect wheat yields the least of the four crops tested. Typical fall and spring weather provide adequate moisture for the wheat crop, and any compaction related moisture stress would be less likely, relative to those crops with growing seasons extending over drier summer months. The low rate of successful hay production is likely attributed to both management problems, especially timely cutting and soil physical conditions. Lack of root proliferation, caused by compact rooting zones, as well as decreased water recharge potential and reduced water uptake, hinder hay production, especially during dry periods. Little difference was evident between three of the four root medium replacement methods (Figure 2) when looking at all crops and all tillage. Dragline soil replacement appears to be lower in crop success for an undetermined reason. Because the coal industry anticipates more compaction to occur on scraper placed soils, this soil replacement method is the method where most deep tillage has been done. Over one-half of the scraper field-years tested were deep tilled; however, less than one-tenth of the bucket wheel excavator fields tested have been deep tilled. No truck shovel replaced fields tested for production have been augmented.

Yields from non-augmented fields appear to be negatively impacted by subsoil replacement methods generally recognized as resulting in the most amount of compaction; i.e., scraper, or by crops most susceptible to water stress (Figure 4 & 6). In those field-years tested that have not received augmentation, 55% meet production requirements. Augmented fields met production 70% of field-years tested (Figure 3). These results seem

Figure 1. Overall Crop Success - All Soil Replacement Methods and Tillage.

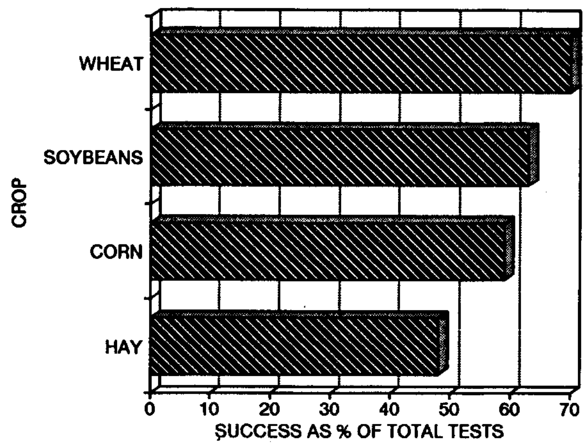
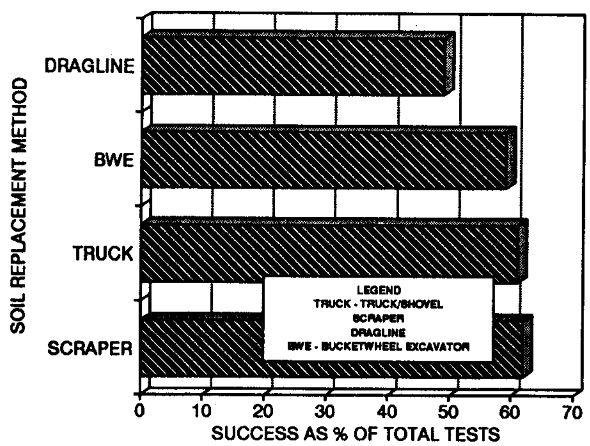


Figure 2. Soil Replacement Methods - All Crops and Tillages.



to support the premise that deep tillage increases the likelihood of fields meeting productivity.

Across the crops examined, those grown on subsoil replaced by the bucket wheel excavator (BWE) had the least variability between crops of field-years meeting production requirements (Figure 4).

One may speculate that the BWE replaces a relatively consistent rooting material, possibly explaining the consistent crop production results. While the production success of all crops is relatively consistent, a review of Figures 4 and 5, reveals that deep tillage of bucket wheel material appears to increase yields for corn. Wide variations of production success across the crop tested under the other subsoil replacement methods without deep tillage are evident (Figure 4).

Various physical conditions of the rooting media, the response of the crops to the rooting media, and weather variations are all potential causes for the variable crop success. Another possible source of variability may be limited numbers of sample points. The largest number of field-years for any crop grown in dragline rooting media was 34 and the largest for truck shovel was 17. One point worth mentioning regarding Figure 4, concerns the low percentage of field-years of wheat that met productivity requirements in truck shovel material. This data was collected from one mine which, due to wet weather conditions near harvest, had reduced crop yields as a result of disease. Figure 6 shows the effect of augmentation to rooting media replaced by the bucket wheel excavator, dragline and scrapers. No augmentation data is available for truck shovel rooting media. Augmentation effects were most noticeable in bucket wheel and scraper replaced subsoil materials. Augmented subsoil replaced by a bucket wheel passed in 100% of the field-years tested for corn and in only 55% of the field-years that were not augmented. One must be careful however, to note that only 8 field-years of bucket wheel data have been deep tilled, but the trend does appear favorable. Scraper replaced subsoil appears to have enough data to draw solid conclusions. Of

Figure 3. Effect of Deep Tillage - All Crops.

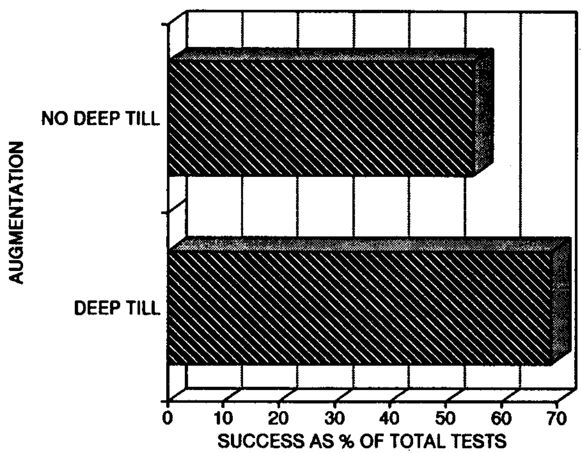


Figure 4. Non-Deep Tilled Crop Successes - Wheat - Hay - Corn - Beans.

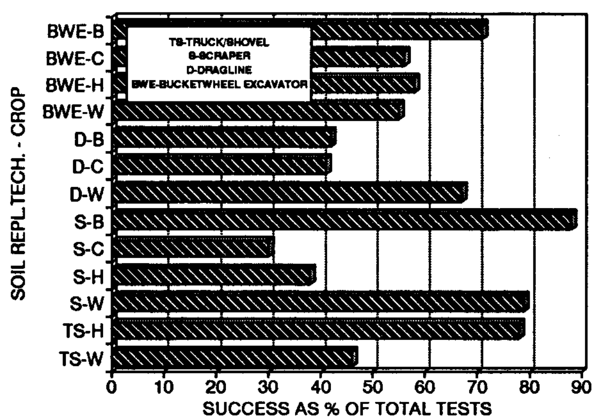


Figure 5. Deep Tilled Crop Successes - Wheat - Hay - Corn - Beans.

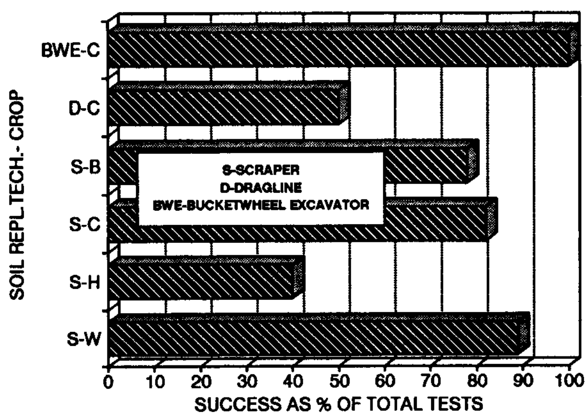
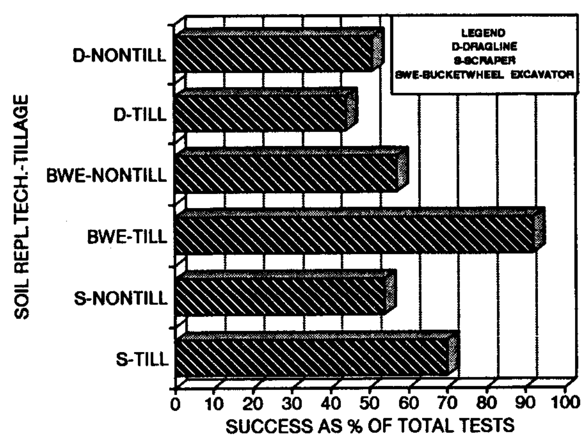


Figure 6. Soil Replacement Methods - All Crops.



the 155 non-augmented subsoil field-years tested an average of 57% met crop production requirements, while an average of 70% of the 171 augmented subsoil field-years made crop productivity. Dragline rooting media had less deep-tilled field-years passing relative to non-deep tilled field years. Again, limited data for deep tilled field-years (only 16 samples) make the conclusions speculative in nature.

In examining trends of all three variables (crop, subsoil replacement method, and augmentation), several prove to be very interesting. Soybeans grown in non-augmented scraper replaced rooting media met productivity requirements in 88% of field-years tested (Figure 4) compared to only 78% of field-years tested for augmented scraper material. However, due to the limited number of data (8 field-years, no augmentation; 15 field-years augmentation) the results are far from conclusive. Scraper replaced hay showed a slight increase in field years meeting requirements after deep tillage (40% to 38%), but such a small difference is likely inconsequential. As stated earlier, the low percentage of hay meeting productivity requirements may be the result in part of limited experience in hay management. Wheat production in scraper replaced subsoil was slightly more successful in augmented field-years relative to non-augmented field-years (87 to 79%).

As previously discussed, weather conditions may influence these results and the success of non-augmented wheat ground may be misleading as to the adequacy of the subsoil physical conditions. As expected, corn field-year success after deep tillage showed dramatic increases in success of production. Both bucket wheel excavator and scraper replaced subsoil appears to have sufficient data to draw such conclusions. Experience with deep tillage of bucket wheel excavator materials and corn productions is much less than on scraper placed materials, but similar positive results for corn were shown by Dunker, et.al.(3) Corn production on dragline replaced rooting media showed a modest increase in percentage of field-years passing after augmentation; however, data is limited. A review of the many fields which passed after deep tillage indicated a history of prior crop failures.

CONCLUSIONS

Approximately 200 field-years of each corn, hay and wheat have been tested for productivity of the 646 field years sampled to date in the state. Scraper replaced rooting media was the most commonly tested root media replacement method. Of the 646 field-years tested, 200 have received some sort of augmentation. Wheat was the most successful crop, (independent of replacement method and augmentation) followed by soybeans, corn and hay. Growing season may influence the success of wheat to date, and management problems likely have contributed to the poor success of hay. Scraper placed subsoils were the most commonly augmented materials. Over all crops and soil replacement methods, deep tillage appears to be having a positive effect on meeting targets; 70% of deep tilled field-years tested met target yields compared to 55% of non-augmented field-years. When looking at crops across root-media replacement methods, bucket wheel excavator material produced relatively consistent success ratios. Crops grown on the other replacement methods showed much more variable success. These results may be due to consistency of rooting materials, effects of weather, reactions of crops, limited number of sample points or interactions of any or all of the above. The low percentage of truck shovel wheat field-years meeting production requirements is in part related to crop disease. Augmentation had the most noticeable positive effects in bucket wheel excavator and scraper replaced materials, but limited number of bucket wheel field-years do not allow concrete conclusions. Dragline subsoils showed variable success and failure in augmented soils, but again sample numbers are small. This also holds true for soybeans grown on scraper replaced augmented soils which was less successful compared to non-augmented soils. Corn fields have definitely tended toward more success in augmented bucket wheel and scraper material, but bucket wheel subsoil is again inconclusive due to limited data. A review of individual fields reveals many of the fields which passed after deep tillage had repeatedly failed prior to the tillage. Over all, data appears very positive for deep tillage effects. Further evaluation is planned to assess the impact of yearly weather stress on individual treatments to refine the conclusions.

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A Review of Procedures OSM Uses to Evaluate and Improve State Regulatory Programs Regarding Prime Farmland Reclamation of Mined Soils

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Abstract. Coal operators and regulatory agencies have the responsibility for insuring that prime farmlands are restored to their premining productivity. The coal operators must demonstrate in permit applications that they have the technological capability to mine and reclaim prime farmland. State regulatory authorities review and then approve these permit applications, if they determine that the applicant can satisfactorily mine and restore the land according to the approved state regulations. The Office of Surface Mining Reclamation and Enforcement periodically reviews permits as part of its oversight responsibilities for each state program. The purpose of the detailed permit approval process and the performance standards placed on the mine operator is to insure that prime farmlands keep their premining productive capability. The number one cause of productivity failures in prime farmland reclamation is excessive soil compaction. Mechanical loosening and incorporation of organic materials into the soil are traditional treatments for compaction.

INTRODUCTION

The Office of Surface Mining Reclamation and Enforcement (OSM) is required to evaluate state regulatory programs to determine their effectiveness. OSM Field Offices often request topic or issue-specific assistance from the Eastern Support Center (ESC) in Pittsburgh or the Western Support Center (WSC) in Denver to implement this responsibility. One topic which has been evaluated by ESC is prime farmland (PFL) reclamation in the states of Illinois, Indiana, Ohio, Pennsylvania, Kentucky, and Alabama. In addition to program oversight reviews, ESC has conducted special PFL studies in Ohio and Illinois. Special studies differ from evaluations by the extensive field testing and statistical evaluation which often occur in a special study.

Background

Public Law 95-87, the Surface Mining Reclamation and Enforcement Act of 1977 (SMCRA), requires the regulatory authority to find in writing that the operator has the technological capability to restore mined PFL. Restoration must occur within a reasonable time, productivity must meet or exceed the levels of yield from non-mined PFL in the surrounding area under equivalent levels of management, and the operator must meet the established soil reconstruction standards. Specifically, state regulations promulgated to comply with SMCRA require the operator to prove he can achieve this performance standard before a permit is issued (30 CFR Part 700, 1991).

OBJECTIVE

The overall objective of this paper is to describe OSM's procedures for evaluating how well state regulatory authorities comply with PFL restoration provisions of their approved programs. In addition, some methods for improving the chances for successful reclamation of PFL soils will be explored.

Evaluation Techniques

OSM uses a three-step approach to evaluate compliance with PFL reclamation requirements. An OSM permit reviewer compares the PFL restoration plan against the requirements of the approved state program. Minesite visits are made to see how well PFL restoration plans compare to actual field operations. Special field studies are undertaken to resolve issues identified in the permit or field reviews.

OSM Field Office Directors in Ohio and Illinois have requested such special studies from the ESC in Pittsburgh. Procedures used in the special studies were similar to those used in field review; but, with a specific objective. These special studies involved a complete review of all prime farmland permits issued during a specific period. A selected number of permits with restored PFL soils were then field sampled using a Giddings soil probe. The findings resulting from the evaluation process are either regulatory or technical in nature, and are discussed below.

In addition to measuring the effectiveness of state programs, existing regulations, and enforcement procedures, OSM evaluates new technology which may help the state and the coal mining industry achieve these standards. OSM research and experimental practice programs endeavor to assess and publicize technology where there is a better or less expensive method of accomplishing successful restoration of PFL soil.

REGULATORY ISSUES

In Ohio, an OSM special study was conducted to determine whether operators were restoring PFL soils to proper thickness (OSM 1986). Several Ohio reclaimed sites were found to have thinner PFL soil than the standard thickness approved in the permit. There were two possible reasons for this shortage of material. Either the operator did not save enough PFL soil material for reclamation; or, there was never enough material on-site before mining to satisfy the PFL reclamation requirements. The latter possibility points to the need for obtaining site-specific information before mining. Published soil surveys are valuable tools for the agriculture industry; but, they are not entirely suitable for mine reclamation. If an operator bases reclamation plans on the published soil surveys, mining may reveal that insufficient PFL soil is present to reclaim to the permitted (or soil survey) thickness.

Several alternatives exist when an operator finds he has less soil than is required for reclamation. All of the alternatives are difficult and expensive. The worst case would involve re-affecting an area already reclaimed to bring the soil thickness to the required level. This would require locating a suitable borrow area on-site, or permitting a new area off-site to acquire the necessary soil for reclamation.

If the operator suspects there is not enough soil present before mining, there are ways to show that the soil is thinner in the disturbed area. The Soil Conservation Service (SCS) will work with the operator to resolve the issue. However, it is very difficult to determine after reclamation what the soil was like before mining.

Another possible solution is to obtain a variance from the thickness requirements. The spoil could be tested to see if it is suitable for use as a growth media to augment the PFL soil. If all efforts to restore the soil fail, the operator may be able to show (through yield data) that premining yields can be met on the restored PFL area. All of these techniques are risky, and there are no guarantees that any of them will work. Therefore, the operator should delineate actual PFL soil thickness before mining. The Ohio Department of Natural Resources has experience with these options, and had success with most of them; but, one site was so inadequate in PFL thickness that any solution short of total reconstruction was infeasible.

In Illinois, an OSM special study was conducted to determine whether the PFL rooting medium was in the textural and chemical range specified by the permit application (OSM, 1987). The Illinois Department of Mines and Minerals routinely approved subsoil substitute material as a growth medium for PFL permits. The department was approving these materials for final soil reclamation based on a specified range of chemical and physical characteristics listed in the permit application. During the OSM special study, a minimum of five composite soil samples were taken at each of six mine sites and sent to a laboratory for analysis. The results showed that all sampled materials were within the range of characteristics originally approved in the permit application. As a result of this study, OSM was able to affirm the Illinois regulatory practice as effective in meeting PFL reconstruction standards.

PFL reclamation techniques have improved steadily since the passage of SMCRA. Prime farmland issues that remain are the result of different interpretations of the regulations. For example, the Soil Conservation Service (SCS) is responsible for setting standards and specifications for mining and reclaiming PFL. The SCS establishes standards for the allowable soil depth to a root-inhibiting layer (such as bedrock). Disagreement, however, can and does occur about replacement depth—especially when the root-inhibiting layer is non-rock (such as fragipans). Some operators base their reclamation plan upon published soil survey data that identifies fragipans as root-inhibiting layers in the soil. However, the SCS has determined that all fragipans that supply more than 0.06inches per inch of available water are not root-inhibiting (7 CFR Part 655, 1985).

The SCS published national standards and specifications that define root-inhibiting fragipans based on their moisture-supplying capability. However, some problems exist because a court decision requires the SCS to publish state-specific standards in the Federal Register before requiring the state to use the standards. This requirement was intended to give all interested parties the opportunity for a public comment period. Unfortunately, it has also delayed instituting the new SCS standards. In order to have some guidelines until standards are published for a particular state, the SCS published a national standard. OSM recognizes the national standards and specifications published in the Federal Register as minimum standards that are more current than those found in the published county-by-county soil survey. Thus, OSM may find state programs less effective than federal requirements where states use published county soil surveys.

The coal industry and the states recognize the SCS as the responsible agency in the area of PFL reclamation. The SCS agrees with the compromise that the 48 inches of rooting material required by the regulations is necessary to achieve PFL target crop yields on mined land. Bond release is problematic at mine sites with less than 48 inches of PFL material. Purely from an economic standpoint, it costs less to replace 29 inches of soil material over graded spoil than it does to replace 48 inches. However, this is only the initial cost, and does not account for any additional cost the operator may incur to meet productivity standards, legal costs associated with violations, and countless hours of staff time.

Generally, field evaluations show that operators are doing a good job of reclaiming PFL soils. However, diligent regulatory inspection of operations is vital in pointing out deficiencies that can be corrected before the operator completely reclaims the site. Despite differing interpretations, a good inspection program will go far towards successful PFL reclamation.

TECHNICAL ISSUES

Prime farmland restoration success is ultimately measured by crop yield. Operators are typically not farmers, and often do not want to grow crops. Therefore, mine operators want some method of predicting crop yields on restored PFL other than by actual crop production.

OSM has funded research to study reclaimed PFL yields in an attempt to develop a predictive tool. Three studies developed models for predicting crop yield based on soil characteristics. A University of Illinois study did not support the concept of predicting crop yield by soil characteristics alone (Jansen and Walker, 1985). Another study is still active at the University of Kentucky. Interim results reported by the principal investigator are encouraging. However, the selection of input variables for the model is critical (Barnhisel and Grove, 1992). Crop yield depends on so many variables being in balance.

This balancing phenomenon is known as equilibrium. All nutrients necessary for plant growth must be in solution before the plant can use them. Some nutrients will be attached to the soil particles and an equal amount will be in solution or dissolved in the soil water. Soil pH and the interrelationship of nutrients affect the availability of nutrients. For example, if nitrogen is in short supply and the plants need potassium, the operator can add potassium and plants will not produce maximum yields until he corrects the nitrogen deficiency. Drought and a host of other natural problems also affect crop yield. These are but a few of the reasons why variable selection for crop yield modeling is so difficult. Understandably, those are also some of the reasons operators do not want to grow crops. Depending on favorable weather for crop production in any particular year is a gamble for mine operators seeking bond release.

The second technical issue in restoring PFL yields is soil compaction. OSM studies of this issue involved several techniques for mitigating compaction. Two studies involved ripping the soil with deep tillage equipment and planting a deep-rooted legume (such as alfalfa) to hold the ripped zones open. Ohio State University had research data showing that alfalfa production increased within one foot on either side of the ripped zone. OSM funded a study where they moved the ripper spacing from four foot centers to two foot centers and planted alfalfa. However, it was extremely wet in Ohio for the three years of the study and the result may be more weather-related than treatment-dependent (McCoy, Barta, and Sutton, 1992). The other study by North Dakota State University involved ripping and deep-rooted plants. This project was affected by several years of drought. Results to date show that deep tillage following redistribution of both topsoil and subsoil, has been the most effective treatment in reducing compaction (Schroeder, 1992). Bulk density also decreased in the topsoil during the first three years following redistribution due to vegetative growth.

In another OSM study, organic material was pneumatically injected into the subsoil as it was deep-ripped to loosen the compacted soil (Saperstein, et al., 1992). While the study results only deal with laboratory data, OSM feels the concept of using organic material to alleviate soil compaction has merit. Organic matter is important because of the effect it has on soil consistency. It is the 'glue' that holds soil particles together, forming soil aggregates. Organic matter increases soil water-holding capacity and its decay leaves channels in the soil for the movement of air, water, and plant roots.

Injection technology is important for correcting existing soil compaction problems. Incorporation of organic material during reconstruction is probably more feasible/practical because the equipment needed for field scale injection of organic material is not available. The researchers were unable to find a manufacturer to develop a prototype field injection ripper. Although one of the injected materials showed some improvement in preventing re-compaction, the results were not statistically verifiable. However, research on non-PFL have shown significant increases in vegetative cover with the addition of organic material such as sewage sludge and wood chips. OSM believes this technology would also benefit PFL restoration.

Almost any organic material is suitable. In addition to the previously mentioned sewage sludge, other researchers have experimented with turning under cover crops into the subsoil before adding the topsoil. This technique is called green manuring. However, known research involving this technique did not statistically prove that green manuring prevented soil compaction on mined lands.

The coal mining industry has also been investigating compaction remedies through mechanical loosening and different placement methods. Inspectors continually evaluate the success of new techniques during routine inspections of active operations. These techniques receive a critical review during OSM's field evaluation of state programs.

CONCLUSIONS

- o The state regulatory authorities have rules in place that can insure successful reclamation of prime farmland.
- o Coal mine operators must do a premining soil thickness examination, because some PFL soils are naturally thinner than 48 inches.
- o Soil compaction is the number one cause of crop failures on restored PFL soils.
- o The primary method used by coal operators to loosen compacted soil is deep-ripping.
- o The technology exists to restore PFL soils to their premining productivity.
- o Some techniques developed by coal operators in PFL restoration and by federally-funded research are improving reclamation.
- o Sewage sludge and other organic additives used on non-PFL mine sites have resulted in a significant improvement in vegetative success.

RECOMMENDATIONS

- o The use of organic amendments to combat PFL compaction should be considered.
- o A cover crop should be grown on the protected PFL subsoil before restoration to add organic matter. Turning under this cover into the subsoil prior to PFL replacement would promote decay and provide channels for the movement of air, water, and roots in the restored soil.
- o Additional study of organic material incorporated into both topsoil and subsoil is needed on reclaimed PFL.

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Assessment of Reclaimed Farmland Disturbed by Surface Mining in Illinois

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Abstract. Illinois procedures for the assessment of reclaimed farmland disturbed by surface mining and reclaimed under various statutes are discussed. The current interim assessment approach maintains the productivity index (PI) of a tract of land at either 90% or 100% of the PI of the soils on the original tract prior to disturbance by surface mining and reclamation. The recommended long-term approach will establish a new tract PI based on the actual soil series present after disturbance by surface mining and all reclamation and productivity restoring treatments have been applied. Before the recommended approach can be implemented, the following tasks will need to be completed: (1) the USDA, Soil Conservation Service in cooperation with the Illinois Agricultural Experiment Station will need to establish additional soil series on surface mined soils with or without reclamation and/or compaction alleviating treatments; (2) a soil scientist should be assigned to re-survey a reclaimed area after all reclamation and productivity restoring treatments have been completed and final bond release has occurred; and (3) crop yields and PI's are assigned by the Illinois Agricultural Experiment Station after an evaluation of the soil properties and plot yield data collected from University of Illinois research plots and by the Illinois Department of Agriculture, Bureau of Farmland Protection and in cooperation with the Illinois Department of Mines and Minerals.

INTRODUCTION

Illinois soils have been disturbed by surface mining for over 100 years. Various techniques for strip mining coal were developed in the last century, and these extraction methods have steadily gained importance. Much of the land surface mined in Illinois prior to 1962 was not reclaimed. The utility of the land was sometimes completely destroyed by surface mining with improper or no reclamation. Since surface mining, reclamation methods, and compaction alleviation treatments vary among companies, locations, and even over time; it has been difficult to develop sufficient soil series to reflect all of these differences.

In the last few years, landowners and other interested parties have suggested that surface mining and reclamation will result in the loss of local tax revenues. In western Illinois, the soils on many tracts have high productivity indexes (PI's); however, after surface mining and reclamation, the tracts in a few counties are shown as soil series mapped on disturbed lands with lower PI's. If county tax assessors were to assign value based on these lower productivity indexes from Circular 1156 (Productivity of Illinois Soils) by Fehrenbacher et al., (1978) as amended by Jansen (1987), the tax revenues collected from the tract would decline. The Illinois Coal Association (personal communication), as well as individual mining companies, believe the assigned PI's of some recently surface mined and reclaimed soils are too low and do not reflect the current reclamation technology in restoring soil productivity. Specifically, the recent compaction reducing treatments have been found to increase total and aeration porosity, increase rooting depth, increase soil water storage and raise crop yields[1/] (McSweeney and Jansen, 1984; Jansen and Hooks, 1988; Hooks et al., 1988). Data collected in the last few years by the Illinois Department of Agriculture, Bureau of Farmland Protection in cooperation with the Illinois Department of Mines and Minerals for bond release under provisions of the 1977 Surface Mining Control and Reclamation Act (SMCRA) law (Public Law 95-87) shows higher crop yields for areas with compaction reducing treatments. If these reclaimed surface mined lands are under-assessed, the public will perceive that reclamation was not successful even when soil productivity was sufficiently restored to meet the 1977 SMCRA law and 1981 Illinois Public Act 81-1015 standards. In Knox County (Illinois), a request for a surface mining permit was challenged by landown-

[1/] I.J. Jansen and R.E. Dunker. 1989. Reclamation for row crop production after surface mining, state of the art. Staff Paper. Department of Agronomy, University of Illinois.

ers at a public meeting held by the Illinois Department of Mines and Minerals (personal communication). One of the reasons cited for requesting that the permit not be issued indicated that reclaimed surface mined land would have lower PI's than the original soils and result in lost tax revenue for the county. In a number of western Illinois counties this has become an important public issue.

This paper outlines current interim approach and the recommended[2/] long term assessment procedures for reclaimed surface mined land in Illinois based on their current productivity.

ASSESSMENT APPROACH - SURFACE MINED LANDS (PRIOR TO 1977)

Lands which were surface mined prior to the 1977 SMCRA law may or may not have been reclaimed. Some areas may have been graded with some topsoil or subsoil material returned. Five soil series (Lenzburg (IL), Schuline (IL), Swanwick (IL), Morristown (KY), and Rapatee(IL)) were set up in the early 1980's and used for mapping surface mined areas. In many counties soil surveys preceded mining events. Rapatee and Schuyline have topsoil (A horizon or darkened surface horizon replacement) and Morristown, Swanwick and Lenzburg do not. The first cropland reclamation standard used in Illinois was Rule 1104 (Surface Mine Land Conservation and Reclamation Act of 1971) (applied in 1971) established a 48 in. rooting medium standard over graded spoil. The top 2 ft. of rooting material could have no more than 20% coarse fragments and no rocks greater than 6 in. in the longest dimension. The clay content could not exceed 40% or not greater than the original soil. Maximum sand content could not exceed 60% if the clay was less than 20%. The underlying 2 ft. could contain no more than 50% coarse fragments and no coarse fragments (rocks) greater than 10 inches. Rule 1104 (Surface Mine Land Conservation and Reclamation Act of 1971 as amended by P.A. 78-1295 effective July 1, 1975) to require that topsoil must be replaced to a depth of 8 in. for HCL and 6 in. for prime or to the depth of original A horizon to a maximum requirement of 18 in. The rooting media must be replaced to a depth of 48 in. or to the depth of original soil if less than 48 in. and must have less than 40% clay, unless original soil had more than 40% clay, and no coarse fragments (rocks) greater than 10 in. This standard existed when the Rapatee and Schuyline soil series were set up. If the soil survey was done before mining and/or reclamation, the productivity indexes (PI's) from Circular 1156 (Fehrenbacher et al., 1978) would be based on the soils present at the time of the soil survey. A re-mapping of these surface mined areas to Illinois Cooperative Soil Survey standards is needed before tract PI can be determined.

On average, county soil surveys are conducted every 30 to 35 years. The only counties which might have surface mined lands which were soil surveyed before surface mining and not reclaimed under the 1977 Reclamation Law would have been published in the late 1950's to 1970's. These areas were small in extent and limited to just a few counties. Most of the early surface mined areas were soil surveyed after mining. The surface mined areas within a county soil survey made after surface mining and/or reclamation activity have been assigned soil series names (County Soil Survey Report) and productivity indexes using Circular 1156 (Fehrenbacher et al., 1978) as amended by Jansen (1987) of the Department of Agronomy (University of Illinois) based on soil properties and limited yield data. These productivity index ratings are used by assessors to determine the agricultural land value and tax assessment.

ASSESSMENT APPROACH - SURFACE MINED LANDS (1977 TO PRESENT)

Assessment of all Illinois cropland is accomplished by local assessors using Illinois Real Property Appraisal Manual (Illinois Department of Revenues, 1988) and periodically updated. The current assessment procedure was authorized by Illinois Public Acts 82-0121 and 84-1275.

At the present time, soils which were mined under provisions of the 1977 Federal Reclamation Law (SMCRA) (Public law 95-87) and Illinois Public Act 81-1015 have been subject to specific standards for topsoil and subsoil replacement for high capability land (HCL) (90% level if grandfathered on or before August 1, 1982 or 100% after that date of original productivity level) and prime farmland restoration (100% level of original productivity level). The reclamation standard for both prime and high capability lands require a minimum of 48 inches of topsoil and rooting material. The primary difference between prime and high capability lands is the replacement requirements from the original soils for prime farmland. A mix of subsoil and substratum may be approved if equivalent to the original B horizon. High capability land has an automatic soil mix approval. Mining operations are under stringent standards for grading, vegetation, etc. The mine operator is under a 5-year liability for meeting reclamation requirements of SMCRA law and 10-year window

[2/]Recommendations do not necessarily represent the official positions of members of the Illinois Cooperative Soil Survey or the Illinois Department of Revenues.

for productivity. However, window may shift if second crop does not meet productivity requirements within 10 years. The 5-year liability for reclamation starts over if land is augmented, i.e., deep tillage greater than 18 inches. During this time he must achieve all reclamation standards including productivity. The productivity of the soils which previously existed are used as the basis for determining the productivity index (PI) from Circular 1156 (Fehrenbacher et al., 1978) for the surface mined lands. The soil survey could have been made before, during, or after the surface mining and reclamation process. The soil maps reflect the soils or materials present at the time of mapping. Soils constructed in surface mined and reclaimed areas differ from the original soils since soil materials are not put back on a tract in the same location and the soil horizons are often mixed. Disturbance disrupts original structural units creating a soil unlike the original. The land value for tax assessment purposes currently remains based on the productivity indexes from Circular 1156 (Fehrenbacher et al., 1978) of the original soils (prior to surface mining) until the soils are remapped. Bond release, however, can be requested after the productivity of the reclaimed soils meet the weather adjusted target goal assigned by the Department of Mines and Minerals and in cooperation with the Bureau of Farmland Protection (Illinois Department of Agriculture). The mining companies are required to meet this weather adjusted goal for 3-crop years (Prime), 2-crop years (High Capability) within a 10-year window after mining. The weather adjustment (Lohse et al., 1985) is made by dividing the county crop yield for the current year by the average annual crop yield for the county determined by multiplying the total acreage of all cropland soils by the long term average crop yield from Circular 1156 (Fehrenbacher et al., 1978). Since 1984, surface subsoiling to a 30 to 52 inch depth has been used by some coal mining companies to alleviate compaction problems, increase rooting depth, increase water storage capacity and raise crop yields. Productivity measurements must be initiated within 10 years after mining; however, the window may shift productivity testing to beyond 10 years (Lohse and Brakken 1987). Once the target goal has been reached for three years for Prime or 2-crop years with High Capability within a 10-year window, the mining companies can request phase II bond release. Phase III bond release occurs when all reclamation is completed, the land is stabilized, and sediment ponds have been removed (62 IL Admin. Code Section 1800.40). However, the land value and taxes would still be based on either 90% or 100% (HCL) or 100% (prime farm land) of the tract PI based on the soil's productivity. This is a current <u>interim approach</u> which helps to: (1) maintain the tax base within the county by assigning the PI of the land at either 90% or 100% of the original tract PI, and (2) accepts the premise that surface mined soils reclaimed under provisions of the 1977 Reclamation Law and Illinois Public Act 81-1015 are being restored to 90% or 100% after July 31, 1982 (62 Il Admin Code Section 1785.17a and 1816.111d) of the original tract PI for HCL and to 100% for the prime farmlands.

The recommended <u>long term approach</u> to assigning PI's to surface mined lands reclaimed under provisions of the 1977 SMCRA law will require the completion of the following tasks:

(1) The USDA, Soil Conservation Service in cooperation with the Illinois Agricultural Experiment Station will assess the need for additional soil series (5 soil series currently mapped in Illinois on surface mined soils with or without reclamation and/or deep tillage). Any new soil series should be established using diagnostic surface and subsurface horizons criteria to classify soils using Soil Taxonomy (Soil Survey Staff, 1975). These new soil series should reflect current topsoil and subsoil thicknesses as well as soil properties altered by subsoiling treatments. Soil series should be sampled for soil characterization. Both field and laboratory data is required.

(2) A soil scientist (Illinois Cooperative Soil Survey) should be assigned to re-survey a reclaimed area at or soon after the time of final bond release using the existing (5 soil series) and any new soil series established by the USDA, Soil Conservation Service such as seven new series currently being considered[3/].

(3) The crop yields and PI's would be assigned by the Illinois Agricultural Experiment Station (Department of Agronomy) after an evaluation of the soil properties (measured in field and laboratory), a review of University of Illinois research plot yields, and an evaluation of certified yield data which has been collected by the Illinois Department of Agriculture, Bureau of Farmland Protection and in cooperation with the Illinois Department of Mines and Minerals.

DISCUSSION

It is quite possible that the PI of a parcel of land reclaimed under provisions of the 1977 SMCRA law and 1981 Illinois Public Act could be lower than either 90% or 100% (HCL) or 100% (prime farmland) of the PI of the original soils on a tract. A likely reason relates

[3/]R.G. Darmody and R.E. Dunker. Classification and mapping of reclaimed mine soils, Fourth Annual Report. 1991. Prime Farmland Reclamation after surface mining, Department of Agronomy, University of Illinois, February, 1991.

to differences in the methods and procedures used to determine long term crop yields. The 1977 SMCRA law and 1981 Illinois Public Act only requires 3 years of crop yields (within a 10-year time period) to meet the target yield which is adjusted for yearly weather differences. The crop yields published by Fehrenbacher et al., (1978) as amended by Jansen (1987) represent the average for all 10 years in the 10-year period and are not adjusted for yearly weather differences. The 10-year time period assumes dry and wet years as well as hot or cold years will occur within the time period that reflect "average" weather conditions.

Even assuming that the few years of crop and tillage treatments are applied to a reclaimed site prior to the collection of yield data, it has not been established that compaction alleviating treatments applied during the reclamation process will continue to provide lasting effects (such as increased macroposity) for 10 years or more after treatment. Only a limited data base currently exists which would address this concern since the compaction alleviating treatments have only been applied since 1982. Compaction alleviation was applied to Amax-Sunspot Ipava Fields in 1982. Nine years of crop growth are available for this mine, although not 9 years of each crop were compared to a standard. The late Dr. Ivan Jansen (1982) believed that once compaction alleviating treatments have been applied and roots have established themselves in the voids (pores and channels) of the previously compacted layers, that the roots would maintain the pore network over time. This will need to be verified with soil property measurements and actual yield data collected years after the compaction alleviating treatments are applied. The PI's, assigned to the soil series mapped on surface mined, reclaimed and treated with deep tillage tract, should predict the average yields future land owners could expect over the next 10- or 20- year period. If PI's are set too high, future landowners will not be able to pay the tax from agricultural use of the reclaimed farmland.

Utilizing this long term approach to assigning PI's to reclaimed surface mined lands, based on soil conditions as they exist, would be consistent with the method utilized on soils not disturbed by surface mining and reclamation. This approach will require a significant amount of time to establish new soil series, sample for soil characterization (laboratory and field), re-map, collect crop yield data, and calculate PI's for the new soil series assigned to the reclaimed surface mined lands with compaction alleviating treatments.

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Development of a Prime Farmland Minesoil in Selectively Cast Overburden in Northeast Texas

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Abstract. Premine overburden characterization through the use of gridded geophysical logs and analytical data from continuous cores was used to compare overburden characteristics to those of native soils at the Winfield surface lignite mine in northeast Texas. Based on the results, regulatory authorities waived replacement of the original soil horizons in favor of selected overburden materials. A postmine soil mapping program suggested that the Grayrock series, the dominant minesoil developing in these materials, qualified as a prime farmland soil. Several years of yield data supported this observation, and Grayrock soils occurring on 1 to 5 percent slopes were declared prime farmland by the U.S. Soil Conservation Service in 1991. These soils comprised 65.9 percent of the mined area, compared to 38.8 percent prime farmland soils within the permit area prior to disturbance. The study suggests that substitution of selected overburden may be a valid choice, particularly in areas where native soils have low to moderate productivity. Postmine soil mapping is recommended as a tool to assist in achieving goals of reclamation planning. A mapping program can also assist in determining the characteristics of postmine soils compared to those of native soils within a given mine permit area.

INTRODUCTION

Regulatory concern for prime farmland in surface coal mining operations rests primarily with recognizing the presence of native prime farmland soils and special requirements for permitting them. A premine soils map and historical land use study is required to identify and locate prime farmland soils and determine their use prior to mining. Mining and restoration requirements for prime farmland call for the separate removal, stockpiling, if necessary, and sequential replacement of the A and B or C horizons. Regulatory authorities in most states may approve substitute materials within the top 4 feet of graded spoil on prime farmland areas, provided this material will create a soil having as good or greater productive capacity than the native soils.

The requirement for a premine soils map has additional benefits in that it provides, prior to disturbance, a permanent record of all soils, including those that qualify as prime farmland. These maps give witness to soil resource conditions before disturbance for mining and serve as a reference base for postmine soils. Development of postmine soil mapping programs is optional for the mining industry. However, few companies choose to initiate such programs. An important benefit of postmine soil mapping in reclamation planning is to provide the location and extent of prime farmland soils after mining. Postmine soil mapping provides a valid procedure for comparing premine and postmine soil quality and, where applicable, can serve as a guide for tax assessment. In addition, a formal postmine soil mapping program recognizes the potential of proper overburden handling procedures for developing prime farmland soils in excess of what was present before mining, particularly where the production potential of native soils is limited. A case in point is the postmine Grayrock soils on the Winfield Mine in northeast Texas. This lignite surface mine, operated by the Texas Utilities Mining Company, is located near Mt. Pleasant, Texas on Interstate 30, about 120 miles northeast of Dallas. Both premine and postmine land uses are dominantly forage crops used for pasture and hay.

NATIVE SOILS AT THE WINFIELD MINE

Thirteen soil map units existed on the Winfield Mine area prior to disturbance. Of these, five dominant soils (Table 1, Part A) comprised 89.4 percent of the area. The remainder of the area consisted of water, borrow pits and eight map units of widely diverse, minor soils.

The Bernaldo (fine-loamy, siliceous, thermic Glossic Paleudalfs) and Freestone (fine-loamy, siliceous, thermic Glossaquic Paleudalfs) soils, which comprised 38.8 percent of the mine area (Table 1), have been designated prime farmland soils as defined by the U.S. Soil Conservation Service in Section 657.5 of the Code of Federal Regulations, dated January 1, 1980. These are very deep, well drained and moderately well drained soils on uplands. Both have a fine sandy loam surface ranging from 8 to 20 inches thick and a loam or clay loam argillic horizon. They are developing in cross-bedded sands, silts and clays from the Wilcox group of Eocene age. Typically, the Freestone soils have a more clayey layer in the lower part of the argillic horizon that moderately restricts internal drainage. Reaction in both soils ranges from strongly acid to slightly acid in the surface and upper subsoil, and very strongly acid to medium acid in the lower subsoil. Although they respond to soil amendments, these soils are not particularly productive.

Nahatche soils (fine-loamy, siliceous, nonacid, thermic Aeric Fluvaquents) in Table 1 consist of very deep, somewhat poorly drained soils on floodplains. They are moderately permeable, and are developing in loamy alluvial sediments of local streams. Strata in both surface and subsurface layers range from silty clay loam to loam. Reaction throughout is typically strongly acid to mildly alkaline, although very strongly acid layers exist in some pedons. Frequent flooding is the main deterrent to crop production.

Table 1. Dominat soils at the Winfield Mine.

SOIL SERIES	% OF AREA
A. PREMINE	
Bernaldo	2.4
Freestone	36.4
Nahatchie	9.5
Wolfpen	6.8
Woodtell	34.3
TOTAL	89.4
B. POSTMINE	
GRAYROCK:	
1-5% Slopes	65.9
>5% Slopes	13.9
TOTAL	79.8

The Wolfpen series (loamy, siliceous, thermic Arenic Paleudalfs) consists of very deep, well drained soils on uplands. The surface layer (A and E horizons) is loamy fine sand ranging from 20 to 40 inches thick that rests on an argillic horizon ranging in texture from loam to sandy clay loam. Reaction throughout ranges from very strongly acid to slightly acid. Parent materials are sandy members of the Wilcox group. The thick, coarse-textured surface is the main limitation to plant yields.

The Woodtell series (fine, montmorillonitic, thermic Vertic Hapludalfs) consists of deep, moderately well drained soils on uplands. These soils have very strongly acid to slightly acid fine sandy loam surface layers 3 to 6 inches thick. These rest abruptly on a very strongly acid to strongly acid clay or silty clay (claypan) argillic horizon. The soils are developing in clayey members of the Wilcox Group. The claypan limits productivity by restricting movement of air, water and roots within the soil.

Table 2 presents data for selected parameters on native and postmine soils at the Winfield mine. These are from the upper part of the argillic horizon (or C Horizon in Grayrock and Nahatche soils). The upland native soils are deeply weathered, as evidenced by thick, well-expressed argillic horizons, described earlier, and the acid nature of the profile. The Nahatche soils, developing in local floodplain sediments, reflect physical and chemical properties of upland soils within the area.

OVERBURDEN HANDLING

During permitting stages at the Winfield mine, topsoil salvage (A horizons) was waived by the regulatory authority in favor of more suitable substitute materials. Recent land use history on the Bernaldo and Freestone series (prime farmland soils by SCS definitions) did not meet prime farmland requirements of historical use as defined in Part 779.138 of the Texas Coal Mining Regulations. Because of this, the permit did not require removal and replacement of individual (A, B and, in places, C) soil horizons on these areas.

Table 2. Selected data from soils at the Winfield Mine*.

SOIL	HORIZON	pH	B.S %	CEC me/100g	SAND %	SILT %	CLAY %	Db g/cc
Freestone	Bt	5.7	79	9.1	39	34	27	1.52
Nahatche	C	4.6	—	13.4	31	37	32	—
Wolfpen	Bt	5.1	—	—	68	12	20	—
Woodtell	Bt	4.6	31	28.4	17	26	57	1.28
Grayrock**	C	7.1	86	33.4	30	42	28	1.40

* Data for native soils are from Soil Resources Report of Mine Permit Area; for minesoils, Cooney et al., 1991.
** Minesoil; remainder are native soils. A dash indicates data are not available.

Accordingly, postmine soils at the mine are developing in a selective overburden material at least 4 feet thick.

Selection of overburden materials for placement in the surface 4-feet of graded spoil was guided by premine studies of geological and geochemical data. Stratigraphic units were correlated and characterized through the use of gridded geophysical logs and analytical data from continuous cores. These units are defined[1] as strata within the overburden that have a distinctive textural composition, a reasonably consistent and predictable stratigraphic relationship with minable lignite seams in the Mine Permit Area, a recognizable geophysical log signature, and a mappable thickness and geographical extent. Weighted averages for significant chemical and physical parameters were calculated for each stratigraphic unit. The location of each stratigraphic unit was plotted along pit centerline cross sections during premine planning. Each unit was evaluated against Texas regulatory guidelines to determine its suitability for use as postmine soil material. These guidelines prohibit use of acid-forming or toxic-forming materials, and place limits on sand and clay content. Table 3, an example of a few of the many parameters evaluated, shows that Unit L2P is discarded due to the negative acid-base accounting value (Smith and Sobek, 1978). This unit, a minor component of the Wilcox Group, consists of partings within a mineable lignite seam. Unit OBU in Table 3, also of the Wilcox Group and a major component of the overburden, consists of reduced, thinly laminated materials that have a higher average silt content and less weathering than the oxidized materials of the native soils. Unit OBU meets requirements for substitute material. Using these procedures for all stratigraphic units within the Permit Area, mining operators are able to selectively handle the most suitable materials for postmine use. Placement of materials is normally performed during dragline operations without earth-handling vehicles, which keeps compaction to a minimum (Holland and Phelps, 1986).

Table 3. Example of overburden evaluation for postmine soil use.

STRAT-UNIT	pH	ABA* t/kt	SAND %	CLAY %	SUIT-ABLE
	MEAN VALUES				
L2P	5.3	-10	13	33	NO:ABA
OBU	7.3	5	21	28	YES

* ABA = Acid-base account in tons $CaCO_3$ /1000 tons of material (Smith and Sobek, 1978).

[1] Personal communication, Jan Sloan, Geologist, Hall Southwest Corporation, Austin, Texas.

POSTMINE SOILS

As mining proceeded at Winfield, a detailed soil survey program was initiated (DeMent & Associates, 1985), first to aid in reclamation planning, and second to determine the kinds of postmine soils being developed. The expansion of this program shows (Table 1, Part B) that, through 1991, the Grayrock series, (fine-silty, mixed, nonacid, thermic Typic Udorthents) established by the SCS in 1984, occupies almost 80 percent of the postmine area (Cooney, et al., 1991). These are very deep, well drained, moderately permeable soils that are forming in reduced overburden materials similar to that characterized by Unit OBU in Table 3. The reduced materials have low value and chroma compared to the oxidized red and yellow colors of native soils. Textures throughout the soil are typically silt loam, clay loam or silty clay loam, with considerably higher silt content than commonly found in native soils of the area. The silts contain considerable amounts of mica. Reaction throughout is near neutral, ranging from medium acid to mildly alkaline. Under forage crops, A horizons with weak to moderate structure in the surface 5 to 7 inches were noted within as little as five years after vegetative reestablishment. Others (Daniels and Amos, 1981) have noted the development of A and Cambic B horizons in Virginia minesoils within relatively short periods of time.

Estimated yield comparisons for Coastal bermudagrass (Cynadon Dactylon [L] Pers.), a major forage crop in the area, and winter wheat (Tritycum aestivum L) are presented in Table 4 for the postmine Grayrock soils and principal native soils within the area. Native soil yield estimates were made by the Soil Conservation Service (SCS) for high levels of management within the area, and are based mainly on the experience and records of farmers, conservationists and extension agents (Soil Conservation Service, 1990). These can vary for

Table 4. Premine - postmine estimated yield comparisons*.

SOIL	YIELDS C. BERM. (tons/ac)	WHEAT (bu/ac)
Bernaldo	7	—
Freestone	6	35
Nahatche	5	—
Wolfpen	5	—
Woodtell	5	35
Grayrock**	8	39

* Rounded to nearest whole number. A dash means not commonly grown. See text for source of estimates.

** Minesoil; Remainder are native soils.

a given year depending on weather, management practices, and the presence or absence of disease and insects. Coastal bermudagrass yields for the postmine Grayrock soils were taken from clipping averages over a period of years in compliance with regulatory reporting programs. Estimated wheat yields were summarized in 1989 by the SCS[2] following three years of study on a 10-acre plot of Grayrock silty clay loam, 1 to 5 percent slopes. Management on the study area conformed to normal farming practices within the area. Due to variances in weather and damage from migratory geese, annual yields ranged from 29 to 59 bushels per acre. The estimated wheat production shown in Table 4 is an average of the 3-year study. In addition to the above, alfalfa (Medicago sativa L) established on a 5-acre plot in 1989 continued to maintain a healthy stand through 1991, in an area where native soils are not adapted to alfalfa production. None of these studies have received statistically valid testing but support conclusions by the SCS that the yield potential of the mined soil is equal to or greater than that of native soils in the area.

Following a review of chemical and physical data and the above yield studies, Grayrock soils on 1 to 5 percent slopes (Table 1, Part B) were declared prime farmland by the SCS in March 1991. These postmine soils, the first to be recognized as prime farmland in Texas, presently occupy 65.9 percent of the disturbed area, compared to 38.8 percent prime farmland soils in the mine permit area prior to disturbance.

SUMMARY

Historically, the consensus among many was that surface coal mining usually had an adverse impact on soil quality. This may have stemmed, in part, from lack of planning during the pre-regulatory period, in which acid-forming, toxic-forming and other undesirable materials were allowed in near-surface layers of graded spoil. In remediation, current regulations might, in places, be too literally applied, especially for the removal and replacement of native soil horizons on prime farmland. Substitute material may be allowed under certain conditions, but few studies demonstrate the conditions under which this is a viable option. Smith and Sobek (1978) postulate that where the original surface layers are deep, soft, dark and neutral (Mollic), as in central Illinois, there is maximum incentive for replacement of surface and near-surface materials. In northeastern Texas, however, this incentive is minimal in the presence of Wolfpen soils (thick, droughty, infertile surfaces) or Woodtell soils (claypan subsoil), particularly where more suitable materials are present within the overburden. Removal and replacement of native soil horizons with such limited productive capacity could severely limit the potential for developing postmine prime farmland. Indeed, most of the postmine 27.1 percent increase in prime farmland soils over premine extent at the Winfield mine is due to substitution of materials more suitable than native soil horizons within the Wolfpen and Woodtell series.

Premine data collection is essential to a successful reclamation program. Planning and permitting stages of mine development should carefully consider viable alternatives for overburden handling and, where justified, allow alternatives. Some alternatives, as in the case of the Grayrock series on selected overburden, not only improve soil quality for crops common to the area, but may also open the way for new cropping systems. In addition to alfalfa, Grayrock soils should also be productive for corn (Zea mays L), grain sorghum (Sorghum bicolor [L] Moench) and soybeans (Glycine max [L] Merr), crops that are not particularly adapted to native soils in the area.

In summary, the Grayrock soils have demonstrated that, where quality overburden conditions exist, careful placement of overburden materials can provide reclaimed areas superior to native soils for crop production. Along with others (Smith and Sobek, 1978), we agree with the principle stated by Borlaug (1976) that "nature's way isn't always good enough". Many soils in the United States have limiting features that can be overcome as a consequence of drastic procedures such as properly planned surface coal mining and reclamation.

Finally, reclamation managers should consider providing for a postmine soil mapping program in their operational planning. Postmine soil maps are extremely useful for reclamation and research planning; they also provide the best means for comparing premine and postmine quality. Without such a program, reclamation personnel at the Winfield mine might never have realized the extent of prime farmland soils being developed through mining and reclamation operations.

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The Development of Restoration Strategies for Prime Farmlands Disturbed by Mineral Sands Mining in the Coastal Plain of The Eastern USA

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Abstract. A large area of the Virginia and North Carolina Coastal Plain has been proposed for mineral sands mining. Much of the area to be mined is productive farmland, and technologies for return to row-cropping after mineral sands mining have not been developed to date. The natural soils of the area are Hapludults and Paleudults with deep sandy loam surface horizons over acidic clayey subsoils. The inherent productivity of these soils is highly dependent on subsoil water retention since summer droughts are common. Simulated tailings and slimes produced from this area appear to be quite suitable for plant growth assuming that they can be blended back together after mining and re-contoured appropriately. The reconstruction of a clay enriched subsoil will be important to long term productivity, and it may also be possible to generate productive topsoil substitutes from re-blended materials. Investigations into mine soils forming in mineral sands tailings in Florida revealed moderate to high levels of subsoil compaction. Mine soil genesis appeared to be quite rapid in these materials.

INTRODUCTION

In August of 1989, we entered into a research agreement with RGC Minerals, Inc. to develop effective restoration strategies for their proposed 5,000 acre mineral sands mining project in the Old Hickory area of Dinwiddie and Sussex Counties, Virginia. Additional deposits have been located in North Carolina. The development of appropriate restoration strategies and techniques for these lands will be challenging. The existing landscape contains a significant acreage of highly productive farmlands, and no research has been conducted to date regarding the return of mineral sands mining areas to rowcrop production.

SPECIFIC RESEARCH OBJECTIVES

1. To characterize the soil-landscape resource associated with the proposed heavy minerals mining operations, and to develop soil interpretations for mining operations and reclamation planning.
2. To document existing soil/crop productivity relationships to establish post-mining productivity targets.
3. To determine the optimum mixture ratio of tailings and slimes for crop productivity, with and without topsoil cover.
4. To develop an integrated materials handling/land restoration plan to maximize the productivity of the post-mining landscape.

REVIEW OF PERTINENT LITERATURE

Reclamation after Mineral Sands Mining

In Australia, heavy mineral sands containing rutile, monazite, ilmenite, and zircon have been mined for over 50 years. Although mineral sands are mined in other parts of the world, the techniques for reclaiming the mined areas were pioneered and developed in Australia (Brooks, 1986). Prior to mineral sands mining in Australia, vegetation is cleared and the A horizon of the soil is stockpiled. The subsoil is then mined with dredges or by conventional dry excavation techniques. Heavy minerals are removed from the soil/sediment matrix by gravity separation in a water slurry, and the tailings which consist of sand are recombined with the slimes (a silt/clay/humic material slurry) and replaced in such a way as to duplicate the former landforms. The topsoil is then returned to the site, and vegetation is established and stabilized (Brooks and Bell, 1984). Many mining areas are returned to native semi-arid shrub vegetation while those in more humid regions are often returned to pasture. Heavy mineral removal produces no toxic wastes, and generally results in a volume loss of less than 5% (Brooks, 1989).

Reclamation of Prime Farmland

Prime farmland is agricultural land that possesses the optimum combination of physical and chemical factors for producing sustained high yields of feed, forage, fiber, and oil crops (Grandt, 1988). Much work has been done on methods of topsoil and subsoil replacement. Jansen and Dancer (1981) compared crop yields on soils with varying thicknesses of replaced A and B horizons to crop yields on graded overburden. They found that on some soils, blending calcareous loess and tills into acid B horizons during overburden handling operations improved their productivity. If the A horizon is replaced, soil structure tends to be better than that found in graded overburden, which results in better seed establishment. These differences in structure tend to disappear over extended periods of time as A horizons develop in the graded mine soil.

A major problem in reconstructing prime farmland after coal removal is that soil and overburden are often replaced by scrapers, which results in soil compaction. Even if topsoil is end-dumped by trucks, a compacted zone often occurs under the A horizon. Much research has focused on trying to decrease the bulk density of this compacted layer by various means.

Powell et al., (1986) found that deep ripping (to 65 cm) combined with the application of 22 to 44 Mg/ha dried sewage sludge produced target corn and sorghum yields on reclaimed prime farmland soils only one year after reconstruction. The pre-mining organic matter content of the A horizon decreases during topsoil removal and storage, and additions of organic materials can help restore the organic matter to original levels. Barnhisel et al., (1988) observed that subsoil ripping did not increase alfalfa yields on reclaimed mined land in Kentucky, and this process did not appear to affect soil bulk density. Liming of the subsoil before the replacement of the A horizon did produce higher alfalfa yields. However, other studies in Illinois have found that deep tillage can reduce soil strength and bulk density, thereby increasing soil productivity.

As mentioned before, the direct application of the results from other prime farmland research to the eastern USA Coastal Plain may be difficult, but it is obvious from the majority of studies that the subsoil conditions after mining are critical to reclamation success. Therefore, mining and materials handling strategies must be developed that insure adequate physical and chemical properties throughout the rooting zone, not just in the topsoil layers.

RESEARCH APPROACH AND METHODS

Soil Mapping and Characterization

Much of this particular landscape has little relief, and detailed mapping is essential since relatively slight changes in micro-topography have a major influence on soil drainage and profile development. The Old Hickory area was mapped in the field at 1"=1000' and was compiled to a rectified 1"=800' base which matches RGC's imagery, maps and data base. For each major soil type in the Old Hickory area, we have selected a "typical pedon" for detailed morphological description and sampling from backhoe pits.

Soil/Crop Productivity Measurements

An important part of the development of mined land restoration plans is the accurate assessment of the pre-mining productivity potential of the various soils over multiple seasons. During 1989 we took yield measurements from several different fields in the Old Hickory area utilizing a weigh wagon, and in 1990 we determined yields at similar sites by hand-harvest of random yield strips.

Florida Tailings Studies

Six representative mine soils developed in sandy tailings at the Associated Minerals mine in Green Cove Springs, Florida, were described and sampled in November 1989 in a preliminary study. An additional seven sites were studied in detail in March, 1991. The sites ranged in age from less than 1 year to approximately 20 years since reclamation. Careful descriptions were made of soil morphology and plant rooting patterns.

Simulated Tailings/Slimes Studies

The development of a set of simulated tailings and slimes was essential for future laboratory and greenhouse studies. Early in 1989, we identified five sites typical of both soils and mineralization for drilling and bulk sampling (Table 1). The entire soil plus geologic profile was drilled with a 36 in well rig, and the combined

Table 1. Soil sampling sites drilled with the well boring rig in the Old Hickory area.

Well	Soil Type	Existing Crop
1	Turbeville	Corn
2	Varina	Peanuts
3	Faceville	Corn
4	Orangeburg	Soybeans
5	Dothan	Soybeans

sample was fed through a pilot plant built on-site to simulate the mineral sands separation process. The tailings and slimes from each of the five sites were then carefully isolated and settled into separate plastic-lined impoundments.

To serve as an "undisturbed" control, Orangeburg topsoil (0-15 cm) was collected from a soybean field near site #4. Orangeburg was chosen as a control because it produced the highest corn yield the previous year. A mixture of topsoil collected from the five sites was also sampled for a second control which would be more representative of the mixture of topsoil materials that would be generated during actual mining.

DISCUSSION OF RESULTS AND PROGRESS

Soil Mapping and Site Characterization

The field delineation of soils was completed in the Old Hickory area early in 1990, and the final compilation of the maps is being completed. A detailed (200 p.) preliminary report documenting the soils, mapping units, and land-use interpretations for the area has been supplied to RGC for field use along with the preliminary field mapping sheets (Hodges et al., 1990). Specific mining related soil interpretations are being developed and include suitability for topsoil salvage operations, road building and wet-weather trafficability, dredging restrictions (pans & stoniness), and other factors.

One of our major objectives over the next year is to work closely with RGC to carefully match our surface soil map with drilling records to reconstruct the geomorphic record for this area. Analysis of these samples will allow us to determine mineral weathering sequences with depth, including clay+silt (slime) profiles, which will directly influence the materials handling and soil reconstruction operations.

The detailed laboratory characterization of the existing soils in the proposed mining areas is important for a variety of reasons. First of all, it provides us with baseline estimates of their properties before mining for comparative purposes. This will be particularly important for our understanding of soil type/crop productivity relationships. Secondly, it will allow us to accurately compare the properties of the mine soils generated by the mining process with the original undisturbed soils. The full characterization data set is given by Hodges et al. (1990) and will be summarized here.

As anticipated, the particle size distribution of the soils varies by soil type and horizon sampled. The older heavily weathered soils (Paleudults), such as Faceville and Turbeville, contain significant amounts of subsoil (Bt) clay to great depths, while those associated with the younger materials below the scarp (Hapludults, e.g. Norfolk, Suffolk) are lower in subsoil clay content. Except where strongly eroded, the thick (> 12") surface horizons (Ap+E) are loamy sands to sandy loams, and are dominated by medium and fine sand. The coarse fragment content of these soils is generally low, except for the subsoil horizons of the plinthic soils (e.g. Varina, Dothan).

Extractable Ca and Mg levels are moderate in these soils due to long term agricultural liming practices. Those soils which do exhibit fairly low levels of Ca and Mg are either extremely sandy, associated with wet or non-agricultural landscapes, or both. Extractable P levels are quite variable in the Ap horizons of these soils, but are medium to high in those which have received fertilization. Subsoil P levels are low to very low, reflecting the low native P content of these Coastal Plain soils. Extractable K content is quite variable, but generally low due to the coarse texture and highly weathered nature of the majority of these soils. The native Ph of all soils is low (< 5) due to long term leaching and weathering, and the cation exchange complex of these soils is dominated by Al.

Soil/Crop Productivity Measurements

Crop yields were taken after a very good rainfall season in 1989 and again in the fall of 1990 following a low rainfall growing season (Table 2). The fields and to some extent the soil type changed between 1989 and 1990 due to crop rotation, but the data do offer a good comparison of the productivity of these soils under good and bad climatic conditions. The influence of irrigation in 1990 was dramatic. Over the next several years it will be important for us to intensify our yield sampling program to include as many soil types and crops as possible.

Florida Tailings Studies

Our preliminary study of the mine soils forming in topsoiled tailings at Green Cove Springs was quite enlightening. Very young profiles (< 2 yr) exhibited

Table 2. Corn Yields on Various Soil Types in 1989 and 1990.

Soil Type	- Corn Yield - 1989	1990
	- bushels/acre -	
Varina	128	82
Dothan/Varina	120	
Varina	153	35
Dothan/Norfolk		145 (Irrig.)
Turbeville/Faceville		53
Orangeburg/Turbeville		81

little or no profile differentiation other than that resulting from topsoiling. The tailings below the topsoil layer showed obvious stratification due to wet settling, and were frequently quite compact. Mine soils between 5 and 10 years in age exhibited much stronger profile differentiation, and all contained a thin continuous band of humate within 20 inches of the surface, often accompanied by a reddish stained zone as well. These layers appear to be the result of humate+iron precipitation, presumably associated with a fluctuating water table. It seems quite remarkable that this spodic-like horizon could form within 5 years, but not totally unexpected since the pore waters of the sandy tailings contain a considerable load of humate and iron dispersed when the native spodic horizon is processed with the sands. The deeper C horizons in these soils were often well differentiated and showed prominent lamination. Several of the subsurface layers were also quite compact.

Rooting in these soils was generally limited to less than 20 inches, and quite often to less than 12 inches. This appears to be due to a combination of a high winter water table and compaction. The compaction observed high in the profile appeared to be due to final grading operations during topsoiling, while that lower in the profile appears to be simply due to wet settling and fill consolidation. In many instances, the bulk density of the subsurface tailings exceeded 1.7 g/cc, a level which may be restrictive to rooting, particularly in unstructured soils such as these. The horizontal lamination present in these subsurface layers may also pose some rooting restrictions. The soils associated with the topsoil layers and upper parts of the sandy tailings developed reasonable structural aggregation within five years, but the deeper tailings remained massive.

Simulated Tailings and Slimes Studies

As expected, the washed tailings and slimes were fairly low in organic matter, extractable P, and cations (Table 3). One very interesting property of the tailings and slimes compared with the native surface soils is that their Ph and exchangeable acidity levels are quite moderate. The only strong difference noted among the various materials was the fact that the CEC of the tailings from sites 1 and 2 were significantly higher in CEC than the others. This was an artificial difference, however, due to the fact that these analyses were run on the first-run tailings before they were re-washed a second time through the pilot plant, and these two samples still contained some slimes.

The mineralogy (Table 4) of the trace clays in the tailings and the slimes was also quite similar with the exception of site 5 (Dothan) which lies on the northern fringe of the Old Hickory deposit. The dominance of the clay fraction by kaolinite along with significant gibbsite is indicative of the highly leached and weathered nature of these materials. Only trace amounts of relatively unweathered 2:1 minerals are present.

The particle size distribution and water holding properties of the individual tailings and slimes were also quite similar (Table 5). The tailings are dominated by medium and fine sand, and show only minor differences among sites. The five slimes are also quite similar with the only major difference being a higher silt content in the Dothan sample. The measured available water holding capacity (0.1 bar minus 15 bar H_2O) was quite low for the tailings. As discussed later, we have discovered several analytical problems in measuring moisture retention in these materials.

Overall, the tailings and slimes processed from the five soil types were remarkably similar to one another in physical, chemical and mineralogical properties even

Table 3. Chemical characteristics of tailings and slimes.

Sample	O.M.	Bray P	Acid Extr. K	Acid Extr. Mg	Acid Extr. Ca	Ph	CEC
	- %-	ppm	ppm	ppm	ppm		meq/100g
			Simulated Tailings				
1	0.1	4	18	48	190	5.6	1.8
2	0.1	4	10	32	140	5.7	1.3
3	0.1	2	8	12	80	5.8	0.6
4	0.1	3	13	23	110	5.5	1.0
5	0.1	2	16	21	100	5.4	1.0
			Simulated Slimes				
1	0.6	4	73	170	550	6.0	5.1
2	0.4	2	54	122	400	5.9	3.8
3	0.4	3	89	160	500	5.7	5.1
4	0.5	5	81	144	430	5.6	4.7
5	1.2	4	102	131	460	5.8	4.5

though their surficial soils were quite different in many cases. We presume that this is due to the homogenizing effect of combining the surface profiles with considerable thicknesses of relatively less weathered deeper sediments.

Characteristics Of Mixed Tailings and Slimes Compared to Native Soils

Compared with the native topsoils, the mixture of 85% tailings with 15% slimes appears to be most similar in physical properties (Table 5). The higher slime ratio mixtures are considerably finer than native topsoils, and more similar to natural subsoil horizons. The pure tailings are extremely low in water holding capacity; water holding increases regularly with slime content, but still appears quite low.

During the initial analysis it became obvious that our lab estimates of field capacity (0.1 bar) water content were quite low, particularly for the mixtures with high tailings content. For that reason, we conducted an in-situ moisture holding experiment to estimate the actual field capacity for these various materials, which generated the data shown under the "Field Capacity" column in Table 5. Due to their coarse nature, the tailings samples apparently contained numerous large diameter packing voids which simply could not retain water against gravity at this low tension. Once the materials are wetted and dried in pots, however, they consolidate significantly and apparently change their packing. This leads to a great increase in micro-porosity and subsequent increases in water holding at field capacity. This "packing behavior" may well explain the high bulk densities observed in the Florida tailings, and may also indicate that maintaining "well drained" conditions may be difficult in the field with these materials.

The chemical characteristics of the various mixtures and native topsoils are shown in Table 6. Compared with the natural soils, the high tailings mixtures are lower in extractable nutrients and CEC, but moderate in Ph. The pH of the slimes composite was around 5.7, so the bulk pH of the original tailings:slimes mixtures decreased regularly with increasing slime content.

Table 4. Clay mineralogy of tailings and slimes from sites 1 through 5.

Site	KaO	ChV	Verm*	Mica	Qz	Gibb
	%					
			Simulated Tailings			
1	60	19	5	2	1	13
2	65	15	5	2	1	13
3	61	15	5	2	1	14
4	65	14	5	2	1	13
5	43	27	5	2	1	22
			Simulated Slimes			
1	63	20	5	2	1	9
2	65	19	5	2	2	7
3	72	12	5	2	1	8
4	64	18	5	2	2	9
5	40	37	5	2	1	15

* Smectites appear to be high charge and are reported with the vermiculite. (KaO = kaolinite; ChV = chloritized vermiculite; Verm = vermiculite; Qz = quartz; Gibb = gibbsite.)

Table 5. Physical characteristics of tailings/slimes mixes and soils. (T=Tailings, S=Slimes).

Growth Media	Moisture retention at: 0.1* bars	15* bars	Field** capacity	Sand	Silt	Clay
	%					
Tailings	1.6	0.9	10.8	97.4	1.0	1.6
85%T:15%S	6.1	3.8	12.5	84.5	7.7	7.8
70%T:30%S	11.2	7.1	13.8	77.0	9.2	13.8
55%T:45%S	16.4	10.7	14.5	59.1	13.2	27.7
Topsoil Mix	9.4	3.5	8.5	78.6	16.5	4.9
Orangeburg	7.3	2.9	7.9	79.6	14.6	5.8

*Moisture desorption method (Richards, 1965).
**In-situ equilibration method, water held in soil core after free drainage into identical material below.

Despite the relatively low pH of the slimes, they contained very low levels of total or titratable acidity. When compared with natural subsoils in the Old Hickory area, the slimes are virtually devoid of reactive Al^{3+}, the major component of exchangeable acidity. Either the Al becomes neutralized during the wet mill processing, or it is simply diluted away by mixture of the weathered acidic surface soil materials with the less weathered deeper sediments. In short, it appears that the processed tailings and slimes will be much less acidic than the existing soils.

SUMMARY AND CONCLUSIONS

The detailed soil mapping of the project area was an important first step in this project. The correlation between soil type and the paleoenvironment of deposition is very strong. Overall, the natural soils of the area are characterized by a deep sandy textured surface horizon over an acidic, clayey subsoil. The surface soils and underlying sediments have been heavily weathered and are very low in weatherable primary minerals.

Our soil/crop productivity efforts to date have shown the tremendous importance of soil water storage and availability to corn production for this region. This effort must continue for multiple seasons so that we can develop accurate site-specific productivity ranges for the dominant soils in crop production.

The tailings and slimes separated from the five major soil types processed were quite similar chemically and mineralogically. The similarity of these materials is due to the fact that they were all derived from upland soils with highly weathered Bt horizons. Other soil types with coarser textured subsurface horizons or those from poorly drained landscape positions where weathering may be less intense may yield significantly different tailings and slimes. On the other hand, if the homogenizing effect of running the entire soil profile and its underlying sediments through the wet mill will result in similar tailings and slimes regardless of original soil type, reclamation planning will be greatly simplified. It also appears that the tailings and slimes generated by the mining process will be less acidic than the natural soil materials, but will be quite low in fertility.

Our findings to date indicate that the tailings and slimes generated by the proposed mining operation will probably have suitable physical and chemical properties for crop production. However, regardless of the inherent suitability of the tailings and slimes themselves, the most important factor governing their long-term productivity for crops will be whether or not the overall mining and materials handling strategy employed will result in a deep, uncompacted, well-drained rooting zone with a moderate slimes content in the subsoil to hold water and nutrients. The Virginia deposit will be quite high in total slimes content, and an adequate method for blending slimes back with the tailings must be developed in order to rebuild productive soil profiles.

Our studies in Florida, while performed in a different soil/geologic environment, have pointed out several important facts. First, there is potential for heavy compaction in sandy tailings when they settle wet. Without significant efforts to loosen and aggregate these materials, they may not be hospitable for deep rooting crops. Distinct subsurface horizons can form in very short periods of time in these materials, indicating that it may be possible to generate differentiated mine soils in a matter of years.

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Table 6. Chemical characteristics of mixes and soils.

	pH	Acid Extractable P	K	Ca	Mg	Zn	Mn	CEC
		ppm						meg/100g
Tailings	6.5	4	8	72	18	0.6	1.1	0.61
85:15 T:S	6.7	3	15	120	31	1.1	4.2	1.15
70:30 T:S	5.1	2	22	180	48	1.0	8.0	2.87
55:45 T:S	5.9	3	29	228	61	1.3	10.9	3.43
Topsoil Mix	5.9	49	64	612	84	1.7	11.5	2.71
Orangeburg	6.2	44	99	432	39	1.9	8.2	2.33

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Physical Root Restriction Prediction in a Mine Spoil Reclamation Protocol

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Introduction. According to Federal regulations, cropland that is prime farmland must be returned to its original productivity after disturbance by mining. For this, the potential rooting depth cannot decrease appreciably. This proposal describes comparisons between potential rooting depth of undisturbed and disturbed soil as part of a more general statement on reconstruction criteria that is under development. Field and laboratory methods are not explored in detail. The proposal has not been tested in the field.

EVALUATION CRITERIA

The criteria that will be used involves prediction of potential rooting. The criteria are based on direct root observations and on structure insofar as would seem appropriate. If rooting depth is not inferable from these observations, bulk density or penetration resistance have been employed. Criteria involving these latter measurements are based on an extensive review of laboratory root growth studies. In order to apply the laboratory data relating root restriction and penetration resistance and to provide criteria that could be applied in the field, it was necessary to obtain relationships among the kinds of tips employed for laboratory and field studies.

Root - Permissive Structure

Reference is made in several places in the criteria to root-permissive structure, defined as: Strong or moderate granular, subangular or angular blocky <10 cm, or prismatic or columnar except very coarse. Evaluation is required while moderately moist or wetter. Underlined terms here and elsewhere are defined in soil survey documents. Bodies formed by mechanical disturbance are considered structural units. Criteria for blocky are applied to fritted structure described by McSweeney and Jansen (1984).

Bulk Density Criterion

Table 1 summarizes 18 laboratory studies of the relationship between root growth and bulk density. In these studies, measurements were made of root elongation into cores having a range in bulk density. The bulk density at maximum root growth and at 0.2 and 0.5 of the optimum is given. Maximum growth in this context is the most rapid or longest elongation of roots into the cores. Maximum growth almost always coincided with the lowest bulk density.

Figures 1 and 2 show relationships between bulk density and clay for 0.2 and 0.5 of maximum growth from laboratory studies of seedling root growth into cores with progressively higher bulk densities. The soil material passed 2 mm and only studies employing a water suction 0.03 MPa or less were included. The most frequently studied plants were those common to temperate agriculture with pea seedlings the most frequent plant material. The disaggregation limits the application of the root restriction studies to those soil horizons that lack structure with repeat distances exceeding 2 mm. The r^2 for silt plus clay was less than for clay alone. The median difference between 0.2 and 0.5 of maximum growth was 0.08 Mg/m^3. The analysis parallels that by Jones (1983) but with some differences in the studies.

The experiments commonly are for unrealistically favorable physical conditions leading to artificially high root growth rates. Since the changes in growth are on a relative basis, a small increase in bulk density may cause a large decrease in root growth. This same bulk density under natural conditions may result in less decrease in root growth. Therefore, it must be assumed that the bulk density for soils in place at 0.2 and 0.5 of maximum growth would be underestimated. The slope of the relationship may be less affected by the initial conditions.

Figure 1. Relationship between clay percentage and the bulk density at 0.2 of maximum root growth for 17 laboratory studies. (Table 1).

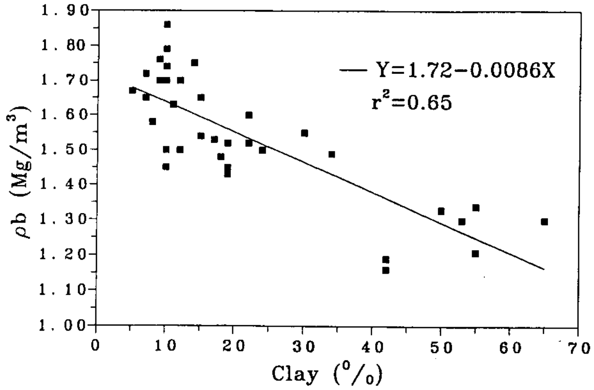

Figure 2. Relationship between clay percentage and the bulk density at 0.5 of maximum root growth for 17 laboratory studies. (Table 1).

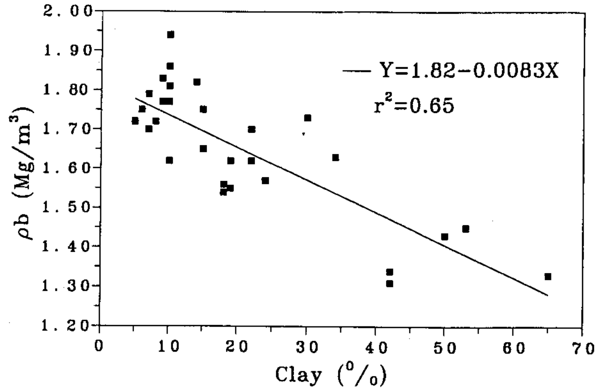

Table 1. Studies of seedling root inhibition related to bulk density arranged by ascending clay percentage and silt percentage within clay percentage.

Clay	Suction	Plant	Bulk Density at Relative Growth 1.0	0.5	0.2	Source
pct	MPa		------- Mg/m³ -------			
5	0.02	Cotton	1.51	1.67	1.72	Bar-Yosef and Lambert(1981)
6	0.01	Cotton	1.56	——	1.75	Jones (1983)[a/]
7	0.02	Cotton	1.55	1.72	1.79	Taylor et al (1966)
7	0.03	Cotton	1.55	1.65	1.70	
8	0.03	Sorghum	1.25	1.58	1.72	Hemsath and Mazurak (1974)
9	0.02	Cotton	1.55	1.76	1.83	Taylor et al (1966)
9	0.03	Cotton	1.55	1.70	1.77	
10	0.02	Cotton	1.10	1.74	1.81	
10	0.03	Cotton	1.10	1.70	1.77	
10	0.03	Soybean	1.55	1.86	1.94	Baligar et al (1981)
10	0.03	Pea	1.29	1.50	1.62	Voorhees et al (1975)
10	0.02	Cotton	1.55	1.79	1.86	Taylor and Gardner (1963)
11	0.007	Pea	1.10	1.63	——	Eavis (1972)
12	0.005	Lettuce	1.25	1.50	——	Carr and Dodds (1983)
12	0.03	Pea	1.50	1.70	——	Barley et al (1965)
14	0.03	Pea	1.55	1.75	1.82	Taylor et al (1966)
15	0.03	Sorghum	1.00	1.64	1.75	Hemsath and Mazurak (1974)
15	0.005	Sugar Cane	1.15	1.54	1.65	Monteith and Banath (1965)
17	0.02	Rye Grass	1.05	1.53	——	Cornish et al (1984)
18	0.01	Yellow Poplar	1.25	1.48	1.54	Simmons and Pope (1987)
18	0.01	Sweet Gum	1.25	1.48	1.56	
19	0.02	Cotton	1.25	1.52	1.62	Taylor et al (1966)
19	0.03	Cotton	1.25	1.45	1.55	
19	0.018-0.03	Wheat	1.17	1.41	——	Masle and Passioura (1987)
22	0.03	Cotton	1.30	1.60	1.70	Tackett and Pearson (1964a)
22	0.03	Cotton	1.30	1.52	1.62	Tackett and Pearson (1964b)
24	0.03	Pea	1.35	1.50	1.57	Blanchar et al (1978)
30	0.02	Sorghum	1.00	1.55.	1.73	Hemsath and Mazurak (1974)
34	0.005	Sugar Cane	1.33	1.49	1.63	Monteith and Banath (1965)
42	0.01	Corn	0.93	1.19	1.34	Phillips and Kirkham (1962)
42	0.001	Corn	0.93	1.16	1.31	
50	0.005	Sugar Cane	1.17	1.33	1.43	Monteith and Banath (1965)
53	0.003	Edible Bean	1.15	1.30	1.45	Asady et al (1985)
55	0.01	Pea	0.92	1.21	——	Voorhees et al (1975)
55	0.01	Pea	0.99	1.34	——	
65	0.005	Pea	1.23	1.30	1.33	Cockroft et al (1969); Greacen and Gardner (1982)

[a/]Personal communication from A.T.P. Bennie in reference cited.

Penetration Resistance Criterion

Penetration resistance at 0.2 and 0.5 of maximum root growth was determined from 16 laboratory studies that used <2 mm soil material at ≤0.1 MPa water suction (Table 2). The tips used in the experiment were either flat-end rods about 6 mm in diameter or 60° cones 1.0 to 3.5 mm in diameter. Comparisons were made between the flat-end rod and both the small 60° cones used in laboratory studies and the larger 30° cones used in the field. To relate the tips, penetration resistance was measured on cores of 11 soil materials of diverse textures at 0.2 MPa water retention and 10 percentage points above. The cores were 15 cm in diameter and were formed as stipulated in the Proctor Density Determination (American Society Testing Materials. 1984). Insertion time increased from 1 to 3s with increasing tip size. The insertion was by hand; measurements are in progress using mechanical insertion. The equations in Table 3 were obtained to convert measured penetration resistance in MPa (x of equation) to the equivalent flat-end rod value (y of equation).

This approach permits the utilization of laboratory studies that employ small 60° cones to establish criteria based on the 6 mm diameter flat-end rod while also making it possible to obtain field measurements with

Table 2. Studies of seedling root inhibition related to penetration resistance arranged by ascending clay percentage and silt percentage within clay percentage.

Clay	Suction	Plant	Penetration Resistance at Relative Growth 1.0	0.5	0.2	Source
pct	- MPa -		------- MPa -------			
5	0.016	Cotton	1.8	1.3	2.6	Bar-Yosef and Lambert(1981)
7	0.02	Cotton	0.06	0.7	1.9	Taylor and Ratliff (1969)
7	0.08	Cotton	0.005	0.4	1.8	
7	0.05	Cotton	0.6	1.3	1.7	Taylor et al (1966)
7	0.02	Peanut	0.005	2.0	4.9	Taylor and Ratliff (1969)
7	0.04	Peanut	0.005	2.0	2.9	
8	0.03	Sorghum	0.2	0.8	1.0	Hemsath and Mazurak (1974)
9	0.02-0.1	Cotton	0.4	1.1	1.5	Taylor et al (1966)
10	0.02-0.07	Cotton	0.6	1.4	1.8	
10	0.03	Pea	1.0	3.3	6.4	Voorhees (1975)
10	0.1	Pea	1.0	3.4	7.3	
10	0.02	Cotton	0.5	1.4	3.3	Taylor and Gardner (1963)
10	0.03	Cotton	0.8	2.2	3.6	
10	0.05	Cotton	1.0	2.1	2.9	
12	0.03	Pea	1.5	1.7	—	Barley et al (1965)
12	0.07	Pea	1.5	3.0	3.6	Hemsath and Mazurak (1974)
15	0.02	Sorghum	0.3	0.8	—	
15	0.005	Sugar Cane	0.3	1.9	—	Monteith and Banath (1965)
17	0.02	Rye Grass	0.3	2.0	—	Cornish et al (1984)
19	0.02-0.07	Cotton	0.6	1.4	1.9	Taylor et al (1966)
19	0.02-0.1	Wheat	1.4	4.6	6.7	Masle and Passioura (1987)
19	0.03	Cotton	0.0	0.4	1.4	Pearson et al (1970)
19	0.03	Cotton	0.0	1.0	—	
19	0.03	Cotton	0.0	1.4	—	
21	0.02	Ann. Rye Grass	0.4	0.8	1.2	Shierlaw and Alston (1984)
21	0.01	Ann. Rye Grass	0.4	3.0	5.1	
21	0.02	Corn	0.4	1.0	1.5	
21	0.1	Corn	0.4	4.1	7.3	
24	0.03	Pea	—	1.2	2.2	Blanchar et al (1978)
28	0.1	Corn	1.6	1.3	—	Mirreh and Ketcheson (1973a)
30	0.015	Sorghum	0.2	0.6	1.0	Hemsath and Mazurak (1974)
30	0.03	Sorghum	0.1	0.7	1.3	
34	0.005	Sugar Cane	0.6	1.3	1.6	Monteith and Banath (1965)
50	0.005	Sugar Cane	0.4	0.6	0.7	
53	0.008	Edible Bean	0.4	3.1	4.3	Asady et al (1985)
55	0.01	Pea	0.1	1.1	—	Voorhees et al (1975)
55	0.03	Pea	0.5	2.1	—	
55	0.1	Pea	0.9	1.7	—	
65	0.005	Pea	0.6	1.4	2.0	Cockcroft et al (1969)

relatively large 30° cones. The median penetration resistance values in Table 4 are from data in Table 2. For the calculation, determinations using small cone tips were converted to the equivalent flat-end rod values with the equations in Table 3.

Locally obtained comparisons between the 6 mm diameter flat-end rod and the penetrometer tip used in the field may be substituted for those in the regulation if there are suitable safeguards that the procedure is reasonable.

As discussed for bulk density, the limiting penetration resistance values in the laboratory root growth studies are probably underestimates because maximum root growth is at unrealistically low penetration resistance.

COMPARISON OF POTENTIAL ROOTING DEPTH

The following evaluation would be applied to each soil series that occurs in the area in question. For each of these soil series, two pedons would be evaluated at locations one mile or more apart and within a five mile radius. If root depth observations or structure are employed in establishing the potential rooting depth, then the observations should be made by a soil scientist.

If rooting depth and structure together are inconclusive, then bulk density or penetration resistance is employed. The intent is to make application relatively inexpensive where possible.

Table 3. Regressions between penetration resistance using the 6 mm diameter flat-end rod (y) and various penetrometer tips (x).

Tip	Number of Comparisons	Equation	r^2
60° cone			
1.5 mm	20	y = - 0.05 + 0.61x	0.95
3.0 mm	20	y = 0.06 + 1.1x	0.95
30° cone			
13 mm	21	y = 0.4 + 0.87x	0.90
20 mm	20	y = 0.06 + 1.4x	0.72[a/]
28 mm	14	y = 0.06 + 1.5x	0.92

[a/] No explanation for lower r^2.

Table 4. Median penetration resistance at 0.2 and 0.5 reduction in root growth from laboratory studies.

Root Reduction	Number of Measurements	Median
		- MPa -
0.2	29	2.1
0.5	39	1.3

The bulk density is for the <2 mm. Water state is not specified. For soil materials that do not have strong structure or contain <20 percent by volume structural units exceeding 2 cm across in the smallest dimension, the bulk density of the fine earth fabric overall cannot be less than what would be obtained by methods 4A1, 4A1d (Soil Survey Staff, 1984). For other soil fabrics, the bulk density of the individual structural units should not be less than would be measured by the foregoing methods.

Each statement to follow has two parts: an informal overview and a formal proposal. The number of stipulations in the formal parts makes the statements complex. This is a reflection of the inherent difficulty in fashioning a proposal that would be regulatory if applied.

Undisturbed Soil

If available, root depth observations are used to establish the potential rooting depth. These observations must be under conditions where tillage compaction, water state, or chemistry are not limiting to root growth. Otherwise structure or bulk density is employed. Bulk density has been made less limiting at greater depth. A default value for the maximum rooting depth is provided if rooting depth is not limiting at a shallower depth. The bulk density values in the criteria are subject to adjustment.

- The potential root depth is the distance from the ground surface to the midplane of the shallowest zone of <u>few</u> roots for the root size class that gives the greatest depth. The plants should be annuals at physiological maturity and form an important crop. Observations must not be on a soil where sufficient compaction by tillage has reduced rooting depth appreciably. Observed rooting depth may be the basis for assignment of the potential rooting depth only if the water state above 120 cm is not restrictive during the growing season. The chemistry to 120 cm must not be more restrictive to root growth than that of the soil under relatively long-term intensive agriculture for the area.
- If observed rooting depth alone cannot be the basis, the shallower is assigned:
  - 120 cm
  - The base of a continuous zone with all parts immediately below 25 cm having one or more of the following:
    a. Root-permissive structure.
    b. <u>Common</u> or <u>many</u> roots of any size.
    c. A moist bulk density less than:
        1.77 - 0.0083 %clay for 25-75 cm
        1.82 - 0.0083 %clay for ≥75 cm

Disturbed Soil

Potential rooting depth may be based on root observations, structure, bulk density, or penetration resistance. Root depths must not be for perennials if the plants for the undisturbed condition are annuals. Criteria based on bulk density or penetration resistance are dependent on location within the rooting depth of the undisturbed soil and are more limiting if the undisturbed soil has root-permissive structure in order to penalize if this structure were obliterated in reconstruction. The soil is wetted to increase the likelihood that the structure described has some permanence. Alive roots are stipulated to exclude those present by recent burial.

- The distance from the ground surface to the midplane of the shallowest zone of few alive roots with the constraints as given for the undisturbed soil.
- If observed rooting depth cannot be the criterion, the depth of potential rooting is the base of a continuous zone from 25 cm that has in all parts one or more of the following:
  a. Many or common roots of any size.
  b. Root-permissive structure after the soil material has been subject by irrigation to the passage of at least one pore volume of water while all parts are very moist or wet. The water added must not change the soil solution chemistry from indicative of dispersion (zone A in figure 3) to non-dispersive (zone B).
  c. Flat-end rod equivalent penetration resistance and/or bulk density that does not exceed the values in Table 5. The penetration resistance cannot be determined while free water is present at the depth of measurement.

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Figure 3. The field of percent sodium and total dissolved solids, both for the saturation extract, divided into a non-dispersive part (zone A), a dispersive part (zone B), and a transitional part (zone C). From Flanagan and Holmgren, (1977).

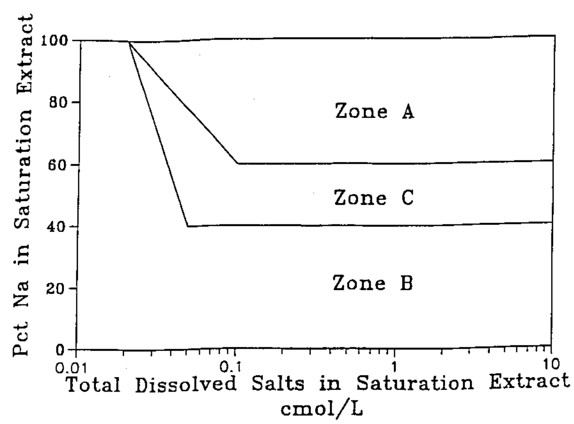

Table 5. Minimum penetration resistance and bulk density indicative of root restriction for disturbed soils. Limits are adjusted for position in the zone of rooting for the undisturbed soil and whether the zone in the undisturbed soil has root-permissive structure.

	Penetration Resistance	Bulk Density
	- - MPa - -	- - - Mg/m² - - -
Upper Half Depth Rooting, Undisturbed soil with root-permissive structure	1.3[b]	1.72 - 0.0086 %clay
Undisturbed soil without root-permissive structure	1.5[a]	Above plus 0.03
Lower Half Depth Rooting, Undisturbed soil with root-permissive structure	1.9[b]	Below minus 0.03
Undisturbed soil without root-permissive structure	2.1[a]	1.82 - 0.0083 %clay

[a] 25 and 50 percentile for ascending order of 0.2 root reduction for 29 laboratory measurements. (Tables 2 and 4).
[b] 50 and 75 percentile for ascending order of 0.5 root reduction for 39 laboratory measurements. (Tables 2 and 4).

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Natural Reformation of Mined Land Reclaimed by Scrapers

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Abstract. The objective of this study was to examine the reformation of surface mined land reclaimed by scrapers. The experiment was conducted at the Arch of Illinois, Inc. Denmark Mine, in Perry County, Illinois. The soils selected for this study were reclaimed in 1977, 1981, and 1985. A non-mined soil and a soil reclaimed by the shovel-truck system in 1989 were included for comparisons. The textural properties of the reclaimed soils were restored to a level similar to that of the non-mined soil, but the reclaimed soils had a higher amount of soluble salts. Soil pH of the reclaimed soils were higher and close to neutral, particularly for soils reclaimed in 1985 and 1989, as compared to the non-mined soil. Generally, the reclaimed soils had a higher bulk density and penetrometer resistance but lower macroporosity. Air permeability, saturated hydraulic conductivity, and cumulative infiltration were highly variable across the selected soils and with depth. However, the results showed that bulk density and penetrometer resistance were lower and macroporosity was higher in the soils that were recently restored. Additionally, extremely poor hydraulic properties were obtained in the reclaimed soils. This study also revealed that the tilth of non-mined soil is far better than that of the reclaimed mined soils, even though some of the mined soils had been reclaimed more than a decade ago.

INTRODUCTION

Coal is one of the most important sources of energy in the United States of America. Surface mining of coal is an important industry in the Midwest. The first coal mining operation was reported by French explorers along the Illinois river in 1679 (Cassidy, 1973). However, the first conventional open pit mining was not started until the 1800's. In Illinois, some 98,400 hectares of land have been affected by surface mining activities (Personeau and Spivey, 1990), of which about 56,600 hectares of the mined land have been reclaimed.

One of the major problems resulting from surface mining operations is the drastic change of the soil profile. Disrupting the soil environment can cause an adverse effect in the hydrologic balance in adjacent areas. The extent of soil disruption depends upon the reclamation methods used. There are many ways to reclaim surface mined land, the scraper, shovel-truck, drag-line, and bucket-wheel excavator systems are the most common methods used in Illinois.

Reclamation of surface mined land creates a new soil profile, generally producing a different soil texture and structure than that prior to mining. These changes can affect both the physical and chemical properties of the soil. However, the major problem with reclaimed mined land is soil compaction. Compaction of soil can destroy soil structure, increase penetration resistance and greatly reduce macroporosity (Jansen, 1982; Potter et al., 1988; and Theseira and Chong, 1989). The reduction in macroporosity can lead to unfavorable hydraulic properties and poor water infiltration, which may increase soil erosion potential. Compacted soil can restrict plant root development and reduce crop yield (McSweeney et al., 1987; and Thompson et al., 1987).

Public law 95-87, also known as the United States Federal Surface Mining Control and Reclamation Act of 1977, requires that soil be restored as close as possible to the conditions prior to mining and also be graded to its original contour. Furthermore, the replaced rooting medium must be of specific textural characteristics that will assist in achieving a productivity level equal to or better than the pre-mining condition.

In the past, most of the mined land research was conducted on recently reclaimed soil or on soil that has been reclaimed two or three years. Some of Illinois mined lands have been reclaimed for more than a decade. In order to have a better understanding and for management of reclaimed mined land, it is important to study the reformation and development of mined soil over time. The main objective of this research was to evaluate surface mined soil which was reclaimed over ten years ago.

MATERIALS AND METHODS

Site Description

The experimental site was located at the Arch of Illinois, Inc. Denmark Mine, in Perry County, Illinois. Prior to mining, the area was predominantly Stoy silt loam (fine-silty, mixed, mesic Aquic Haplaudalf). After mining, the soil was classified (Grantham and Indorante, 1988) as Swanwick (fine-silty, mixed non-acid, mesic Typic Udorthent).

The sites selected for this study included soils reclaimed in 1977, 1981, and 1985 by scrapers. A non-mined Stoy silt loam and a soil reclaimed in 1989 by the shovel-truck method were also included for comparative purposes (the detailed reclamation procedures used for the shovel-truck site are not available). On all the reclaimed areas, fertilizers were applied shortly after the reclamation work was completed. Additionally, mixed vegetation including sweet clover (Melilotus spp.) and smooth bromegrass (Bromus inermis Leyss) was planted as cover crops to reduce erosion. However, the soil reclaimed by the shovel-truck system was planted in wheat (Triticum aestivum L.) and the non-mined area was covered mainly with tall fescue (Festuca arundinacea Shreb.) at the time of sampling.

Sampling Methods and Experimental Procedures

Soil samples were collected in the summer of 1990. In this study, it was assumed that the variability within each selected soil was negligible. On each soil, an area of 15 x 15 m was used and a grid was developed at intervals of 3 m. Penetrometer resistance was measured at each intersection of the grid. Therefore, a total of 36 penetrometer resistance measurements were obtained on each selected site. The penetrometer resistance was measured to a depth of 100 cm using a constant velocity auto-recording penetrometer (Hooks and Jansen, 1986). After the penetrometer resistance measurements were taken, a 3 x 4 m pit was excavated at the center of the selected area using a backhoe. Profile classification was performed by soil scientists from the Soil Conservation Service at Jackson County, Illinois. The pit was dug to a depth of 1.5 m. Three undisturbed core samples (10 cm long and 7.94 cm in diameter) were obtained at 20 cm increments using a portable undisturbed soil core sampler (Chong et al., 1982) to a depth of 80 cm. The undisturbed cores were obtained from the north, west and east sides of the pit. Composite soil samples were also collected from the same depths at each layer for textural and chemical analyses.

Soil pH was determined by the potentiometric method using a 1:1 soil-water mixture (Eckert, 1988). The tritrimetric Walkley-Black method was used for measuring soil organic matter (Schulte, 1988). Electrical conductivity was measured on a 1:2 soil-water mixture by a conductance bridge (Jackson, 1958). Extractable phosphorus (P) was extracted with Bray P-1 solution and analyzed on a spectrophotometer at 660 nm (Knudsen and Beegle, 1988). Exchangeable potassium (K) was extracted with neutral 1 N ammonium acetate and analyzed on a flame photometer (Brown and Warncke, 1988).

Soil physical properties studied included penetrometer resistance, soil texture, infiltration, saturated hydraulic conductivity, macro- and microporosity, air permeability and bulk density. Soil texture was determined by the hydrometer method (Gee and Bauder, 1986). The infiltration of each soil core was measured by the ponding method (1 cm of water head), in the laboratory. After measuring infiltration, the soil core was saturated by capillary action over a period of 24 hours. The saturated hydraulic conductivity (K_{sat}) of the soil was determined under a unit gradient set-up. After K_{sat} was measured, the soil core was weighed and then put on a tension table at a suction of 250 cm of water for 48 h to determine macro- and micro-porosity of the soil. The 250 cm of water suction was arbitrarily chosen as the boundary between micro- and macro-porosity. The soil core was immediately weighed after it was removed from the tension table to prevent moisture loss by evaporation. Air permeability (K_{air}) was measured by a constant pressure gasometer (Corey, 1986).

After K_{air} was determined, the soil core was oven dried at 105°C to determine bulk density. Total porosity of the soil was calculated from the relationship of bulk density and particle density. Particle density was assumed to be 2.65 g/cm^3.

RESULTS AND DISCUSSION

The textural results and description of each soil profile are shown in Table 1. The results reveal that the texture of the reclaimed soil has been restored to a textural class comparable to that of the adjacent non-mined soils. However, the mined soil had a sub-angular blocky and firm structure, which was quite different than that of the non-mined soil. Detailed description of all the profiles is available elsewhere (Moroke, 1991)[1].

Table 2 gives the data of selected soil chemical properties. The pH values of the non-mined soil and the soil reclaimed in 1977 and 1981 decreased with increas-

[1] Moroke, T.S. 1991. Pedological evaluation of reclaimed surface mined soil. M.S. Thesis, Plant and Soil Science Department, Southern Illinois University at Carbondale, IL.

Table 1. Soil textural analysis results and classification ofselected soils at the Denmark mine area, Perry County, IL

Depth (cm)	% Sand	% Silt	% Clay	Textural Class
		Non-mined Stoy Silt Loam		
0 - 20	18.95	66.75	14.30	Silt loam
20 - 40	13.72	49.54	36.74	Silt clay loam
40 - 60	12.11	43.10	44.79	Silt clay
60 - 80	17.98	47.21	34.81	Silt clay loam
		1977 (Scraper)		
0 - 20	20.35	58.30	21.35	Silt loam
20 - 40	25.65	54.73	19.62	Silt loam
40 - 60	28.40	49.16	22.44	Loam
60 - 80	22.65	49.90	27.45	Clay loam
		1981 (Scraper)		
0 - 20	21.55	49.03	29.42	Clay loam
20 - 40	19.72	48.84	31.44	Silt clay loam
40 - 60	17.03	52.13	30.84	Silt clay loam
60 - 80	19.67	50.85	30.84	Silt Clay loam
		1985 (Scraper)		
0 - 20	14.54	58.78	26.68	Silt loam
20 - 40	23.21	48.45	28.34	Clay loam
40 - 60	23.11	44.05	32.84	Clay loam
60 - 80	27.20	45.02	27.78	Loam
		1989 (Shovel-Truck)		
0 - 20	30.04	45.26	24.70	Loam
20 - 40	18.14	53.84	28.02	Silt clay loam
40 - 60	36.96	35.01	28.03	Clay loam
60 - 80	37.57	34.44	27.99	Clay loam

Table 2. Mean of chemical properties measured on the selected reclaimed mined soil at the Denmark mine area, Perry County, IL.

			Scraper	-------- Shovel - Truck --------		
Depth(cm)	N	Non-Mined	1977	1981	1985	1989
			pH (1:1)			
0 - 20	6	7.3	7.1	7.2	5.0	6.0
20 - 40	6	5.4	7.3	6.8	6.0	6.0
40 - 60	6	4.0	7.1	4.7	7.2	7.8
60 - 80	6	3.9	5.3	4.1	7.5	7.7
			Organic Matter (%)			
0 - 20	6	1.11	1.26	1.12	1.21	1.34
20 - 40	6	0.46	1.11	0.31	0.70	1.51
40 - 60	6	0.28	0.30	0.52	0.26	0.10
60 - 80	6	0.21	0.30	0.21	0.29	0.10
			Electrical Conductivity (mho x10^{-5})			
0 - 20	6	11.5	+	10.0	10.0	15.5
20 - 40	6	+	10.0	10.0	15.5	27.0
40 - 60	6	+	34.0	21.0	44.5	41.0
60 - 80	6	+	43.0	22.0	75.0	43.0
			Potassium (Kg/ha)			
0 - 20	6	306.5	220.6	194.5	156.8	263.2
20 - 40	6	203.8	100.8	102.7	146.0	149.7
40 - 60	6	165.8	100.8	126.9	132.5	132.9
60 - 80	6	53.1	93.3	166.5	141.5	151.6
			Phosphorus (kg/ha)			
0 - 20	6	24.1	53.2	28.6	32.5	45.9
20 - 40	6	20.2	36.4	23.0	33.0	44.8
40 - 60	6	25.2	20.7	21.3	26.3	12.9
60 - 80	6	34.7	15.1	42.0	27.4	11.8

+ Denotes value close to zero.

ing soil depth, and the non-mined subsoil (40-60 cm) had the lowest pH values among all soils selected in this study. The pH of the soil reclaimed in 1985 and 1989 increased with increasing depth (up to pH = 7.8). The results also revealed that the reclaimed mined soil generally had a high pH, except in the subsoil (40-80 cm) reclaimed in 1981.

Table 2 also indicates that soil reclaimed by scrapers had a slightly higher organic matter (OM) content than the non-mined soil and soil reclaimed by the shovel-truck method. Higher organic content in the reclaimed soils may be a result of the mixing of soil materials during the reclamation processes and/or decomposition of planted vegetation. For the soil reclaimed by the shovel-truck system, Table 2 shows that the OM content was higher than 1.3% in the surface soil (0-40 cm) but dropped sharply to a value of 0.1% below the 40 cm depth. Overall, the organic matter contents of all the soils studied were within the average range found in most southern Illinois farm lands.

The electrical conductivity (EC) data indicated high variation among the reclaimed soils. EC for reclaimed soils were relatively higher than non-mined soil. This may be due to the accelerated weathering of minerals exposed to the atmosphere by the mining processes. Electrical conductivity of the non-mined soil was extremely low and was undetectable below a soil depth of 20 cm. The non-mined soil was not disturbed by mining operations, therefore it is very likely that soluble salts may have leached out and/or leached deeper down in the soil profile.

Chichester and Hauser (1991) observed increased phosphorus (P) in the reclaimed soil as compared to the non-mined soil. Similar results were found in this study. Generally, there was a decrease of P with increasing depth in the reclaimed soil, but, the opposite pattern was observed for the non-mined soil. Phosphorus content showed less variation within and among the soils studied in contrast with Potassium (K) content. The non-mined soil had a higher K content in the 0 - 60 cm layer than the reclaimed soil. Perry county is classified as a region of low supplying power for P and K (Illinois Agronomy Handbook, 1990). The results obtained in this study show that both P and K values of the reclaimed soils remained in the low level.

The results of bulk density, total porosity, macroporosity, micro-porosity and penetrometer resistance are shown in Table 3. Bulk density tended to increase with increasing depth for both reclaimed and non-mined soils. Furthermore, bulk density of the non-mined soil was significantly lower than that of the reclaimed soil (alpha = 0.05). Even though the results of bulk density showed a large variation between soils and depths, the linear relationship of bulk density versus depth was significant for soil reclaimed in 1977, 1981 and 1989, but, no linear relationship was found for the non-mined soil and soil reclaimed in 1985. The soil reclaimed by scrapers in 1977 had the highest bulk density (average was 1.74 g/cm^3) in the subsoil (20 to 80 cm), followed by soil reclaimed by the shovel-truck system (1.71 g/cm^3), soils reclaimed in 1985 and 1981, and the non-mined soil (1.49 g/cm^3). Soil reclaimed by the scrapers in 1981 and 1985 had an average bulk density of 1.65 g/cm^3 in the subsoil. These results indicated that soils reclaimed in 1981 and 1985 were less compacted, which might be attributed to the improvement in restoration techniques and/or awareness of the compaction problems. Since the non-mined soil had the lowest soil bulk density, it had the highest porosity (average was > 42%) of all soils studied. In contrast, the total porosities of all the reclaimed subsoil (from 20 to 80 cm) were less than 39%, except for the soil reclaimed in 1981 by scrapers in the 20-40 cm depth. Most of the pores in the reclaimed soil were micropores, particularly for soil reclaimed by the shovel-truck system. More than 99% of the porosity was determined to be micropores. The macro-porosity in the reclaimed soil was much lower than that of the non-mined soil, especially for soil below the 40 cm depth (see Table 3). The decrease in macro-pores may have a tremendous impact on the movement of water and air in soil, since preferential flow of these fluids depends upon the availability of macro-pores. The amount of macro-pores is generally related to the degree of soil compactness. This relationship shown in Figure 1, is a strong inverse relationship between bulk density (BD) and macro-porosity ($= 49.85\ BD^{-5.37}$, with $r^2 = 0.61$) was obtained. Therefore, it can be concluded that the reduction of porosity in a compacted soil is usually at the expense of macro-pores.

The average penetrometer resistance versus depth for each of the selected soils are presented in Figure 2 (each point on the graph is an average of 36 measurements). The figure reveals that there was little variation in penetrometer resistance in the surface layer (0 - 20 cm) among soils studied. However, below the 20 cm depth, the soil reclaimed by scrapers in 1977 had the highest penetrometer readings (>2 MPa), followed by soils reclaimed in 1981 and 1985. Figure 2 also indicates that the non-mined soil and soil reclaimed in 1985 by the scraper had very similar penetrometer readings. The soil reclaimed by the shovel-truck system had the lowest penetrometer resistance. It should be recalled that soil reclaimed by the shovel-truck system had the second highest bulk density of all the soils studied. Generally, a high soil bulk density value results in a high penetrometer reading. However, in this case the results obtained were an exception to the rule. This discrepancy might be due to variable water content in soils when the penetrometer readings were taken. The average penetrometer resistance and the degree of water saturation in each soil depth at sampling are given in Table 3. It shows that soils reclaimed in 1985 by scrapers and shovel-truck method had the highest water content at the time of sampling. Soil restored by the shovel-truck method had a water content close to field saturation. It has been reported that penetrometer resistance of 2.0 MPa will severely impede plant root proliferation (Taylor and Gardner, 1963). Figure 2 reveals that soils reclaimed in 1977 and 1981 by the scraper method had penetrometer readings over 2.0 MPa in the 20 - 80 cm depth. Although there was a wide variation in penetrometer resistance among all the soils studied, Figure 2 clearly shows that soils reclaimed more recently had lower penetrometer resistance values.

Table 4 presents the results of infiltration, saturated hydraulic conductivity, K_{sat}, and air permeability, K_{air}. The results of these three physical properties were highly variable across depths and among the selected soils. Generally, the non-mined soil had a relatively higher infiltrability of water. In contrast, the infiltration of all the reclaimed subsoil was very low, and for some layers water movement stopped before one hour. The saturated hydraulic conductivity of all the soils in the 0 to 20 cm was less than 0.51 cm/h. The non-mined subsoil (40 - 60 cm) had a K_{sat} value higher than 2.5 cm/h. But, as the soil depth increased, like all the subsoil in the reclaimed land, the K_{sat} became very low and most of the time the K_{sat} was close to zero. The same result was observed for air permeability.

Table 3. Mean of physical properties measured on the selected soil at the Denmark mine area, Perry County, IL.

			Scraper	-------- Shovel - Truck --------		
Depth (cm)	N	Non - Mined	1977	1981	1985	1989
			Bulk Density (g/cm³)			
0 - 20	3	1.47	1.42	1.49	1.41	1.58
20 - 40	3	1.50	1.62	1.54	1.69	1.73
40 - 60	3	1.45	1.78	1.65	1.67	1.65
60 - 80	3	1.52	1.82	1.70	1.64	1.76
			Total Porosity (%)			
0 - 20	3	44.70	46.37	43.64	46.84	40.31
20 - 40	3	43.57	38.93	41.63	36.07	34.82
40 - 60	3	45.13	32.74	37.87	36.86	37.70
60 - 80	3	42.60	31.43	35.69	38.03	33.44
			Microporosity (%)			
0 - 20	3	32.63	30.73	34.68	32.07	33.29
20 - 40	3	33.70	31.63	32.37	31.00	33.84
40 - 60	3	37.66	29.34	34.63	32.39	37.23
60 - 80	3	37.14	31.18	34.91	31.58	32.49
			Macroporosity (%)			
0 - 20	3	7.99	10.39	5.93	9.68	3.71
20 - 40	3	++	5.05	5.40	4.34	0.68
40 - 60	3	5.16	2.32	2.40	2.19	0.93
60 - 80	3	3.35	2.64	2.07	2.88	0.94
			Soil Strength (MPa)			
0 - 20	36	0.74	0.72	0.56	0.68	0.75
		(0.82)*	(0.63)	(0.79)	(0.75)	(0.85)
20 - 40	36	1.07	2.10	1.28	1.27	0.85
		(0.81)	(0.77)	(0.69)	(1.00)	(0.96)
40 - 60	36	1.33	2.52	2.18	1.29	0.85
		(0.81)	(0.91)	(0.83)	(0.92)	(0.95)
60 - 80	36	1.48	2.26	2.10	1.34	0.88
		(0.90)	(0.99)	(0.92)	(0.87)	(1.00)
80 - 100	36	1.52	2.35	1.97	1.47	2.43

* Values in parenthesis indicate the degree of saturation of the soil at the time of sampling. Water content data at 80 - 100 cm were not available.

++ Denotes damaged core samples.

Figure 1. The relationship between macroporosity and bulk density. The data in the figure is a combination of all the core samples obtained from the selected soils (both mined and non-mined) on the Denmark mine, Perry County, IL.

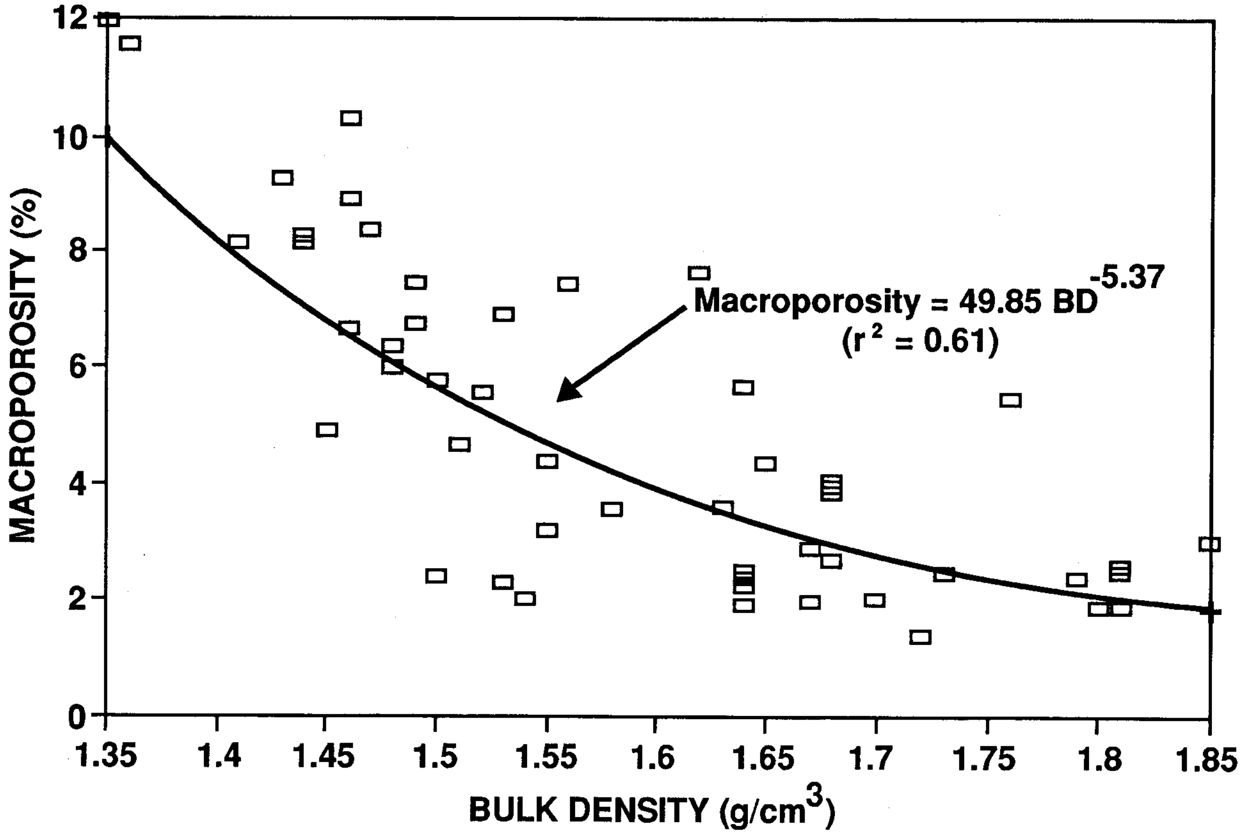


Table 4. Air permeability, 1 hr cumulative infiltration, and saturated hydraulic conductivity measured on soils selected at the Denmark mine area, Perry County, IL.

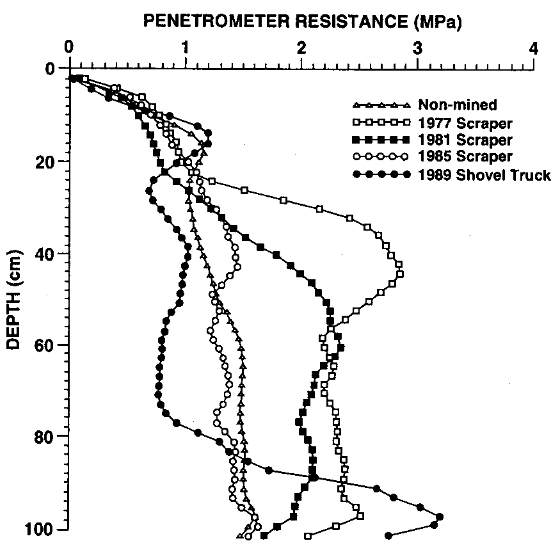
Depth (cm)	N	Non-Mined	Scraper 1977	-------- Shovel - Truck -------- 1981	1985	1989
			Air Permeability (10^{-11} m^2)			
0 - 20	3	1.50	1.74	3.49	1.99	0.84
20 - 40	3	+	0.09	1.83	0.63	+++
40 - 60	3	3.06	0.69	0.97	+++	+++
60 - 80	3	1.51	1.99	+++	0.22	+++
			Cumulative Infiltration (cm) at 1 h			
0 - 20	3	0.81	1.64	4.72	1.38	0.80
20 - 40	3	+	0.36	0.57	0.39	0.56
40 - 60	3	2.52	0.31	++	0.20	++
60 - 80	3	2.73	++	1.13	0.54	0.93
			Saturated Hydraulic Conductivity (cm/h)			
0 - 20	3	0.34	0.32	0.51	0.38	0.25
20 - 40	3	+	**	0.23	**	+++
40 - 60	3	2.54	+++	**	+++	+++
60 - 80	3	**	+++	+++	+++	+++

+ Denotes damaged core samples.
++ Denotes infiltration stopped before 1 hr.
+++ Denotes value too low to be measured.
** Denotes that two out of three samples were measured zero.

CONCLUSIONS

The texture of the rooting media in the soils reclaimed by the scraper and the shovel-truck methods was restored comparably to that of the non-mined Stoy silt loam. The pH of the reclaimed soils was generally higher than that of the non-mined soil, particularly for soil below the 20 cm depth. Organic matter and phosphorus content among the soils studied were not significantly different, but potassium was highly variable among the soils and between depths. In the reclaimed mined soils, soluble salts were high and increased with increasing depth. In contrast, soluble salts were very low in the non-mined soil, especially in the subsoil region (20 - 80 cm). The penetrometer resistance data showed that the soil reclaimed by scrapers in 1977 had the highest soil compaction followed by 1981, 1985, and the non-mined soil. The soil reclaimed by the shovel-truck system had the lowest penetrometer resistance because of high soil water content at the time of sampling. In contrast, the soil reclaimed by scrapers had a lower bulk density than that of the soil reclaimed by the shovel-truck system. However, there is a general decrease in soil penetrometer resistance in soils that were recently reclaimed. The majority of the pores found in the reclaimed soil were micropores, which limited the movement of both air and water in the profile. This conclusion is also supported by results obtained for infiltration, hydraulic conductivity and air permeability experiments. Additionally, macro-porosity was shown to be inversely related to bulk density. This study also revealed that the tilth of the non-mined soil is far better than that of the reclaimed mined soils, even though some of the mined soils had been reclaimed more than a decade ago.

Figure 2. Average soil penetrometer resistance profiles of selected soils on the Denmark mine, Perry County, IL (each curve was an average of measurement).



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Development of a Soil Productivity Index for Use in Prime Farmland Reclamation

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Abstract. Under current federal regulations coal operators are required to grow row crops to prove the productivity of reconstructed prime farmland soils as a prerequisite for Phase III bond release. This study was conducted to determine whether a calculatable index based on the physical and chemical characteristics of the reconstructed soil could be used to accurately predict soil productivity based on corn yield. Soil parameters measured for 30 locations on the River Queen Mine in Muhlenberg County, western Kentucky included: bulk density, cone penetrometer resistance, water holding capacity, phosphorus, potassium, exchangeable aluminum, particle size distribution, and pH. Wheat and corn yield data will be used to further analyze the model as they become available.

INTRODUCTION

In recent years considerable interest has been generated in the concept of developing indices to predict the productivity of croplands on the basis of their physical and chemical soil characteristics. The potential usefulness of such productivity indices (PI) is of special significance as applied to soils reconstructed following the surface mining of prime farmlands.

Current federal regulations governing prime farmland reclamation do not allow release of Phase III bond any sooner than 5 years after the requirements of Phase I have been met. Bond release is primarily contingent on demonstrating that row crop yields with adjustments for weather conditions have met standards for 3 years. As an evaluation criterion, crop yield is not only dependent on the quality of soil reconstruction, but also on weather conditions, and on several options that can be classified under "management practices."

Therefore it has been proposed here that a productivity index might:

1) more accurately evaluate the adequacy of soil reconstruction, and
2) provide a mechanism which could potentially allow bond release by the fifth year after Phase I bond release, provided adequate ground cover has been established, and reclamation standards other than yield have been met.

Thus, bond release might be achieved without necessitating the actual growing of corn and other crops as required by most midwestern states as is the case in Kentucky. This would also reduce risks for the coal company for annual planting, management, and harvesting of row crops, and associated soil disturbance, as often companies may have to contract these responsibilities to a third party.

With these goals in mind, a PI model was developed that represents an outgrowth of models put forth in the literature within the past 10 years. The model of Wollenhaupt (1985) in particular was tailored to meet the yield prediction needs associated with reconstructed prime farmland soils in the Midwest. Select parameters previously unmodelled were introduced because of their significance in soil restoration. These include subsoil: soil fertility (phosphorus and potash), soil acidity (exchangeable Al), and cone penetrometer resistance. Consideration in their selection was given to incorporating the fewest number of parameters that are not only predictive of root growth, but also provide a cost-efficient means of measurement to the operator.

The model is being tested for soil profiles and corresponding yield data extracted from a data set of 30 locations from a test field at the River Queen site in Muhlenberg County in western Kentucky over a 3-year period.

LITERATURE REVIEW

Requirements for Reconstructing Prime Farmland Soils Following Mining

Soil replacement regulations which affect prime farmlands following mining require that the minimum depth of soil and substitute material used in soil reconstruction be 48 inches (122 cm), "or a lesser depth equal to the depth to a subsurface horizon in the natural soil that inhibits or prevents root penetration, or a greater depth if determined necessary to restore the original soil productive capacity" (Kentucky Natural Resources and Environmental Protection Cabinet, 1986).

Productivity Indices

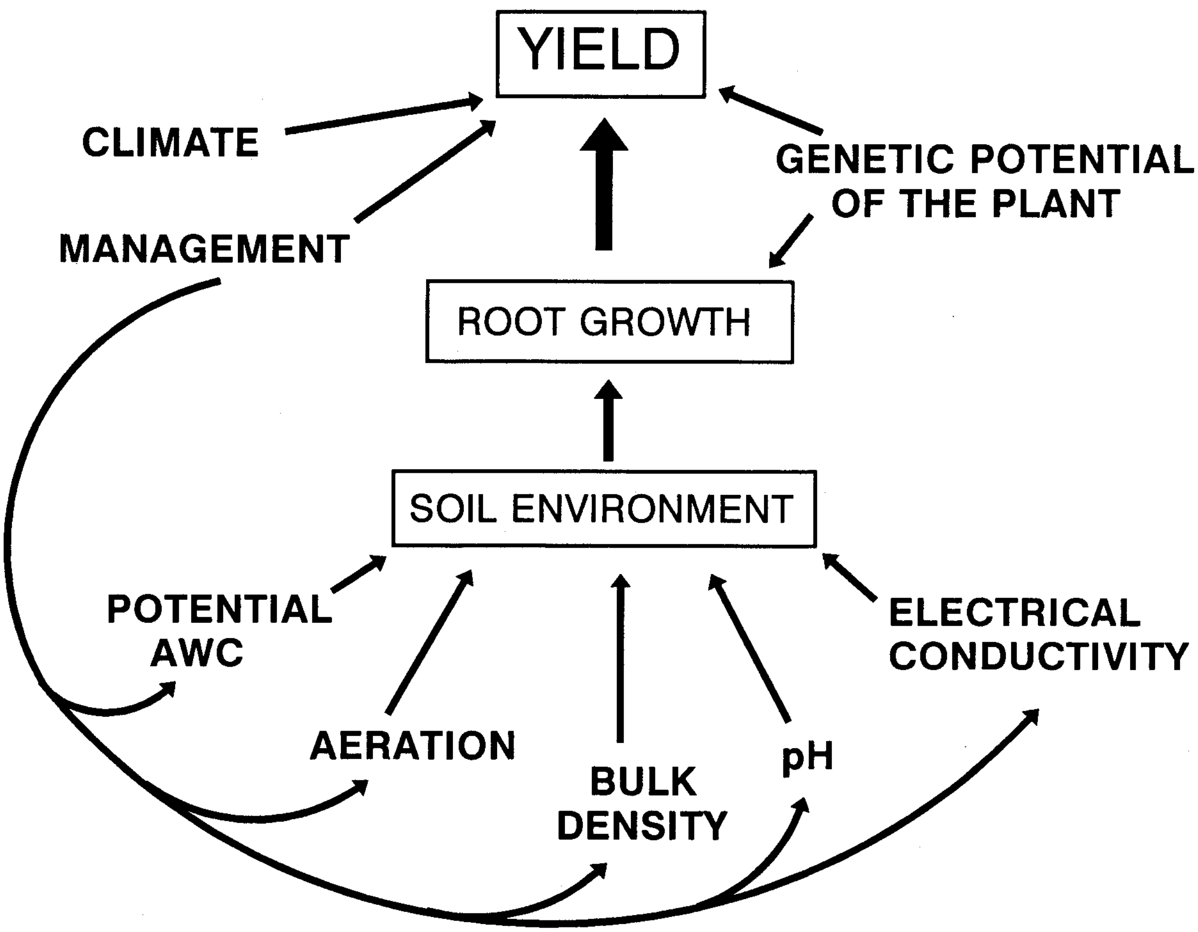
Over the past 60 years in the United States, a variety of quantitative expressions have been proposed for the purpose of inducing soil productivity from soil characteristics. These indices have been developed in response to specific needs in agricultural land use planning and in the equalization of land values and tax assessments (Huddleston, 1984).

In 1979, Neill proposed an index such that yield was assumed to be a function of root growth which, in turn, was a function of soil environment (Figure 1). Her model evaluated horizons of soil profiles in terms of potential available water storage capacity, aeration, bulk density, pH, and electrical conductivity and the sufficiency level of each to promote root development. The product of these five sufficiency factors was then multiplied by a depth-dependent root weighting factor per horizon based on an ideal corn root development model. The sum of these products over a given soil profile was defined as the productivity index.

Pierce et al., (1983) built off the concept proposed by Neill (1979) and streamlined it to consider only three major soil characteristics: bulk density, available water, and pH. Bulk density sufficiency was redefined to reflect various soil texture classes. While Neill assumed an ideal rooting depth for corn of 200 cm, Pierce et al., (1983) used a critical soil rooting depth of 100 cm. Both models assumed that nutrients are not limiting to plant growth.

In 1985, Wollenhaupt refined the model further by considering the four root development sufficiency factors of bulk density, available water, pH, and electrical conductivity. Adjustments to sufficiency equations were made. Bulk density was considered to be dependent not only on texture class, but also on hydraulic conductivity. Available water was redefined as water held between the matric potentials of 10 and 1500 kPa. The sufficiency of pH was modified after that reported by Pierce and associates and the sufficiency of electrical conductivity was modified after Kiniry et al., (1983).

Figure 1. Conceptual model presented by Kiniry et al., (1983).



Wollenhaupt (1985) normalized the root distribution curve between the upper and lower horizon boundaries, solved the integral for centimeter increments, and found the relationship to approach the power function

$$Y = ax^b$$

where:

y = root weighting factor
a, b = constants
x = horizon depth.

Soil Factors Introduced in This Study

The soil characteristics of P and K concentrations, total acidity, and cone penetrometer resistance were introduced as sufficiency factors in the model developed herein. Subsoil fertility was considered essential to adequate root growth and beyond the control of surface management techniques.

Total acidity, especially exchangeable Al, of the subsoil has been demonstrated to be a significant factor which can potentially impair crop yields (McKenzie and Nyborg, 1984). Acidity can be a consideration in the soils and overburden materials associated with coal surface mining in the Midwest.

Newly constructed prime farmland soils commonly exhibit excessive soil strength and an absence of continuous macropore networks. Consequently, root growth is often severely inhibited because of provisions for water movement, aeration, and root system extension are lacking (Hooks and Jansen, 1986).

Data presented by Thompson et al., (1987) indicate that within each soil horizon, as cone penetrometer resistance increases, average root density decreases. This effect appears to be most profoundly evidenced in the 67-88 cm and 89-110 cm layers studied for soils at the Captain Mine in Perry County, Illinois on fields where soil reconstruction was achieved using the mining wheel-conveyor spreader system.

LABORATORY METHODS

Experimental Site

An experimental site was established on the River Queen Mine operated by Peabody Coal Company near Central City in Muhlenberg County, in western Kentucky. The site selected for "prime" soil reconstruction was a preparation plant waste gob on which a 50 cm layer of mine spoil had been deposited. The spoil was composed of a mix of acid, sandstone, shale, mudstone, and siltstone.

Reconstruction of a subsoil was accomplished by depositing a Sadler silt loam soil to a depth of 50 cm over the spoil. A 20 cm topsoil layer composed of silt loam A horizon material (organic matter l 1.5%) was deposited during the Spring of 1988. All soil deposition was accomplished through the use of scraper pans (Semalulu, 1992).

The field was ripped to 60 cm depth prior to fertilizer additions with a 'Rome' ripper that has four shanks approximately 75 cm apart. Phosphorus and K fertilizers were surface broadcast. The area was planted to wheat (Pioneer 2555) in the fall of 1990 and harvested in June, 1991. Soil samples and penetrometer measurements were taken in early July from the same areas where wheat yields were collected.

Soil Sampling

A tractor-mounted Giddings coring machine was used to collect soil samples on a grid comprising 30 field locations. Two samples at each location were taken approximately one foot apart; each core was to a maximum depth of 30 in (76 cm). Sampling locations were separated by 80 ft (24.38 m) longitudinally and 50 ft (15.24 m) laterally.

Cone penetrometer resistance was introduced to the productivity index model as a potentially efficient alternative to bulk density as a measure of soil compaction. Although bulk density sampling can be accomplished across a wider range of soil moisture conditions, data collection and analysis are more time-consuming than that required for cone penetrometer resistance. Cone penetrometer resistance measurements can be rapidly accomplished when soil is sufficiently moist. Both penetrometer resistance and bulk density have been demonstrated as adequate predictors of root system performance, especially in the deeper regions of the root zone (Thompson et al., 1987).

Soil Testing

Soil tests were performed by the Dept. of Agronomy and the Soil Testing Laboratory of the University of Kentucky.

Bulk density was determined using a procedure modified from the core method described by Blake and Hartge (1986). Water pH was determined using a glass universal electrode (Van Lierop, 1990; Eckert, 1988; and The Council on Soil Testing and Plant Analysis, 1980). Exchangeable aluminum was determined employing the titration method of Yuan (1959). Available P and K were determined by the Mehlich III (M-3) extraction (Tucker, 1988a; Tucker, 1988b).

Percent sand, silt, and clay were determined by the pipet method of Gee and Bauder (1986). Water-holding capacity was determined using a standard method developed by Klute (1986). Water-holding capacities were calculated from moisture values obtained at field capacity and wilting point.

A continuous-recording cone penetrometer was used on a tractor-mounted Giddings coring machine at a constant rate of 29 cm/s. A 30° right-circular cone point of 6.45 cm (1 in) cross-sectional area was employed after the methods of Hooks and Jansen (1986). Measurements were recorded on chart paper. A replicate measurement at each sample location was taken. Areas under the recorded curves were integrated as representative of psi of resistance.

PI MODEL DEVELOPMENT

The productivity index model tested is a sum of products. Each soil test value is assigned a sufficiency factor ranging between 0 and 1.0 which indicates adequacy to promote root growth. The product of these sufficiencies for each soil layer in a profile is multiplied by a root weighting factor which is a function of soil depth. The PI for a single soil profile is the sum of the PI's for the soil layers which comprise that profile. Conceptually the model is depicted in Figure 2.

The equation for the subject model is:

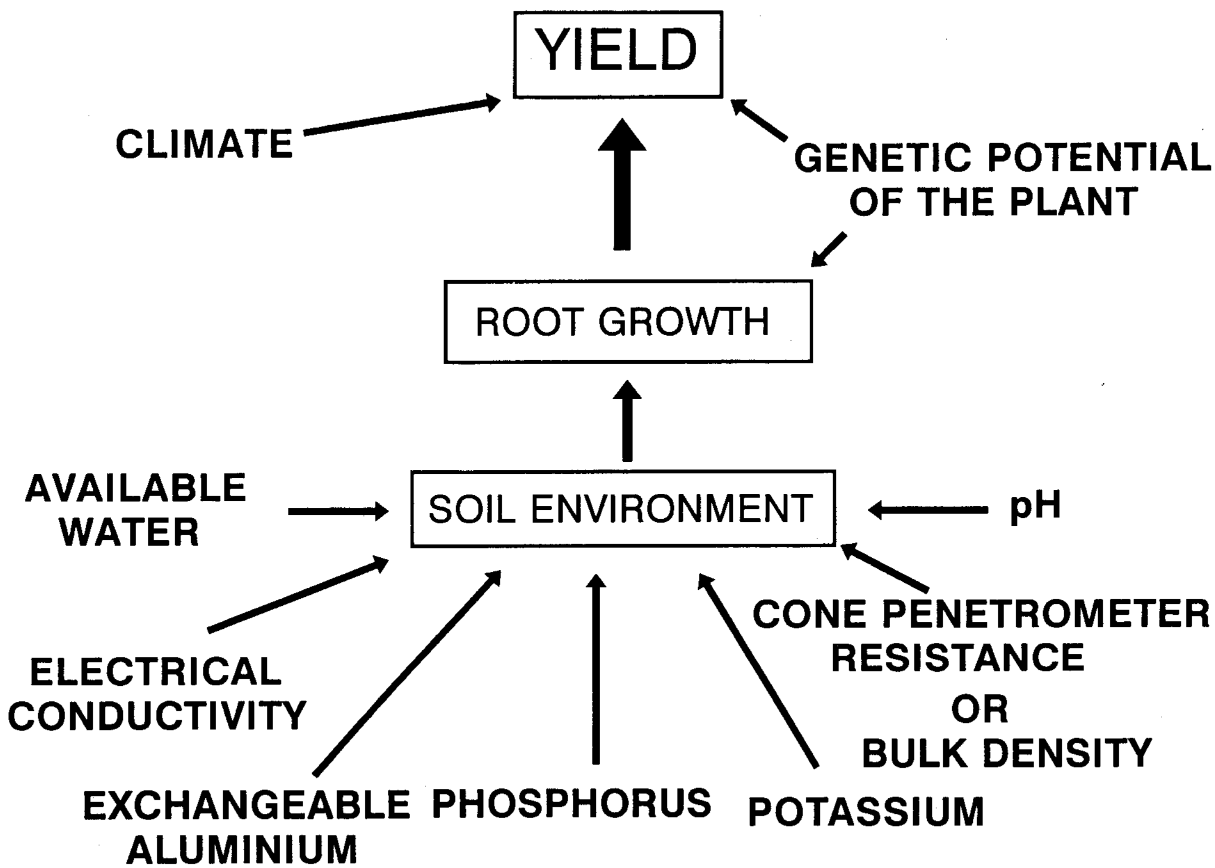
$$PI = \sum_{i=1}^{i=n} [BD_i \cdot AWC_i \cdot pH_i \cdot EC_i \cdot P_i \cdot K_i \cdot EA_i \cdot CPR_i \cdot WF_i]$$

where:

n = number of layers in the soil profile
BD_i = bulk density sufficiency for the ith soil layer
AWC_i = available water holding capacity sufficiency for the ith soil layer
EC_i = electrical conductivity sufficiency for the ith soil layer
P_i = phosphorus sufficiency for the ith soil layer
K_i = potassium sufficiency for the ith soil layer
EA_i = exchangeable aluminum sufficiency for the ith soil layer
CPR_i = cone penetrometer resistance sufficiency for the ith soil layer
WF_i = root weighting factor for the ith soil layer.

Sufficiency equations developed by previous workers were adopted for: bulk density (Wollenhaupt, 1985), available water (Kiniry, 1983 and Wollenhaupt, 1985), pH (Pierce et al, 1983 and Wollenhaupt, 1985), and

Figure 2. Revised conceptual model.



electrical conductivity (Kiniry, 1983 and Wollenhaupt, 1985). For the purpose of this application electrical conductivity and hydraulic conductivity (in relation to its effect on bulk density sufficiencies as calculated in the model) were assumed to be non-limiting in their effect on root growth.

Sufficiency curves were developed for the remaining parameters. Linear equations were used to describe the sufficiency functions of both P and K (University of Kentucky, 1990). Because it has been shown by Woodruff and Parks (1980) and others that corn roots do not obtain P and K below certain soil depth, it was assumed that:

IF UDEPTH $\geq$ 61 THEN KSUFF = 1:PSUFF = 1

where:
UDEPTH = upper depth of the ith soil layer in cm
KSUFF = potassium sufficiency
PSUFF = phosphorus sufficiency.

Based on soil test data (Univ. of Kentucky, 1990) it was assumed that K and P soil test data in excess or within the medium soil test range were sufficient for plant root development.
Therefore,
IF P > 60 THEN PSUFF = 1
IF K > 300 THEN KSUFF = 1.

Furthermore, the following ranges in P and K values were used to define linear equations relating soil test values to sufficiency.
IF P $\geq$ 30 AND P < 60 THEN PSUFF = .0833P + .5
IF P $\geq$ 10 AND P < 30 THEN PSUFF = .0125P + .375
IF P $\geq$ 0 AND P < 10 THEN PSUFF - .04P + .1
IF K $\geq$ 200 AND K < 300 THEN KSUFF = .0025K + .25
IF K $\geq$ 90 AND K < 200 THEN KSUFF = .0023K + .3
IF K $\geq$ 0 AND K < 90 THEN KSUFF = .0044K + .1

Findings from subsoil acidity studies that have examined the effect of exchangeable aluminum on forage yields from the crops of barley and alfalfa as conducted by McKenzie and Nyborg (1984), Hoty and Nyborg (1972), and Webber et., al (1982) were used as a basis for determining the relationship of exchangeable aluminum to exchangeable aluminum sufficiency, as follows:
IF EA = 0 THEN EASUFF = 1
IF EA > 0 AND EA < .033 THEN EASUFF = -.03EA + 1
IF EA $\geq$ .033 AND EA < .22 THEN EASUFF = -.012EA + .975
IF EA $\geq$ .22 AND EA $\leq$ .27 THEN EASUFF = -.08EA + 2.075
IF EA > .27 THEN EASUFF = .1
where:
EA = exchangeable aluminum in meq/100g
EASUFF = exchangeable aluminum sufficiency.

Soil strengths demonstrated as limiting and non-limiting to the development of ideal corn root distributions with depth were developed after yield data presented by Thompson et al (1987). The following assumptions were made and incorporated into the model:
IF LDEPTH $\leq$ 15 THEN CPRSUFF = 1
IF CPR $\leq$ 200 THEN CPRSUFF = 1
IF CPR $\geq$ 400 THEN CPRSUFF = 0.1
IF CPR > 200 AND CPR < 400 THEN CPRSUFF = -.0045 CPR + 1.9

where:
LDEPTH = lower depth of the ith soil layer in cm
CPRSUFF = cone penetrometer resistance sufficiency
CPR = cone penetrometer resistance in psi

The root weighting factor was taken after Wollenhaupt (1985, and personal communication, 1992), such that

$WF = .04295\ (\text{soil depth})^{0.68351}$

The model is programmed in GW BASIC for batch processing of data on IBM PC-compatible equipment.

Model Verification

Productivity indices generated by the model will be tested for their predictive capability by determining their correlation coefficients with corn yield at the 5 and 10 percent confidence limits.

PREDICTIVE CAPABILITY OF THE MODEL

Assessment of the predictive capability of the model in terms of accurately forecasting corn yield continues. Corn production figures from the subject site should be available in the late Summer of 1992. Wheat harvest data (Figure 3) obtained during June, 1991, are being used on a preliminary basis for the purpose of model testing.

Selected soil sampling points representing a range in wheat yields have been used to test the proposed model. These same data were used as input for the model developed by Wollenhaupt, and trends and differences between the two sets of calculated PIs noted. In all cases, electrical conductivity was assumed to have a sufficiency of 1, and hydraulic conductivity was assumed to be non-limiting in the calculation of an adjusted bulk density based on soil texture.

Because of the preliminary nature of the model at this printing, no further discussion will be offered. Testing of the model using both wheat, and eventually corn yield data is scheduled. Results from the wheat and perhaps data from other laboratories will be reported in August, 1992.

SUMMARY

A productivity index model which represents an expansion of current thought and a tailoring to the specific mine reclamation needs of midwestern prime farmlands was developed. It considered the added effects of soil fertility (P and K) acidity in the form of exchangeable Al, and cone penetrometer resistance as an optional measure of soil compaction. Corn yield data will not be collected until the late summer of 1992 for the soil conditions measured. Analysis of the model continues.

ACKNOWLEDGMENT

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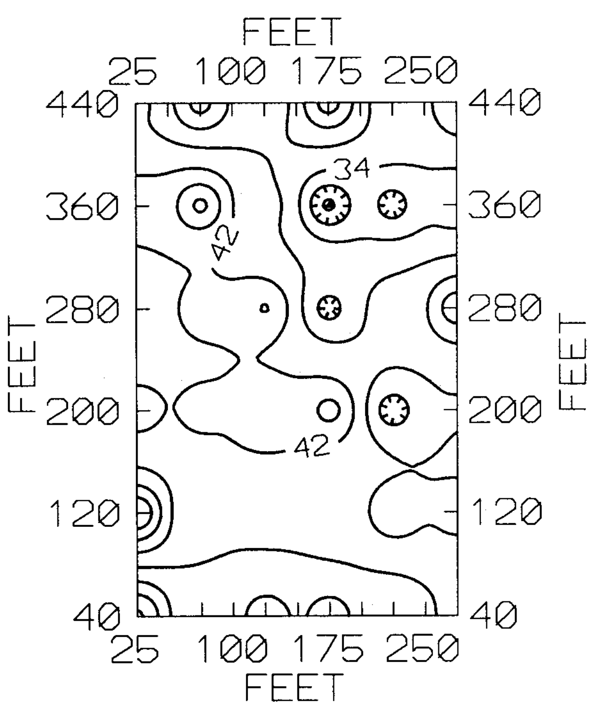
Figure 3. Wheat yield at River Queen Mine 1991.



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Bulk Density Response to Placement Methods and Remedial Measures in Reconstructed Prime Farmland Soils[1]

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Abstract. Experiments were conducted in cooperation with Peabody Coal Company at two surface mine sites. Soil bulk density was determined at multiple depths and locations within experimental plots using both volumetric core samples and gamma ray attenuation.

At the River Queen site, a Sadler silt loam soil was reconstructed in distinct A & B horizons during 1983 using scraper placement and dozer grading. For plots planted immediately in notill corn, subsoil bulk density has gradually decreased over time. Multiple ripping of some plots did not affect this rate of decrease. Initial planting in alfalfa with no ripping produced a slight decrease in subsoil bulk density, whereas a, more dramatic decrease was indicated for plots initially planted in black locust.

Two methods were investigated for placement of Sadler and Belknap silt loam prime farmland soils at the Gibraltar site. Plots were constructed in 1982-83 using (a) scraper placement and dozer grading of both A & B horizons and b) truck placement of A & B horizons by end dumping with grading of each horizon by dozers. In all cases, ripped plots exhibited lower bulk density than non-ripped plots. There was no significant difference between the two placement methods studied with regard to subsoil bulk density.

INTRODUCTION

Successful reclamation of prime farmland soils was specifically mandated by the landmark U.S. Surface Mining Control and Reclamation Act (Public Law 95-87,m 1977). The U.S. Soil Conservation Service was charged with identifying specific criteria for evaluating productive potential of prime farmland and thereby insuring compliance with the law. The result has been the identification of target yield requirements for specific crop-soil-location situations.

Soil bulk density is widely recognized as a physical property which is indicative of crop production potential (Barnes, 1971). Regulatory agencies have recognized the adverse effects of excessive soil bulk density upon productivity and have encouraged development of methods for controlling compaction during soil reconstruction. The objective of this study was to evaluate various means of avoidance and remediation relative to the long-term productivity of reconstructed prime farmland soils.

[1] The investigation reported in connection with a project of the Kentucky Agricultural Experiment Station and is published with the approval of the Director of the Experiment Station as paper no. RIS 91-48.

REVIEW OF LITERATURE

The adverse effects of excessive soil compaction have been extensively documented during the last two decades (Barnes, 1971 and Soane et al., 1981). This problem is exacerbated by the growing use of large agricultural field machinery with relatively high axle loading ($\geq$ 9 Mg). Taylor et al. (1980) showed that such equipment can cause compaction of subsoil below the depth of conventional tillage even when surface contact pressure is no greater than that of smaller equipment. The effect of such deep compaction has been shown to persist for decades (Graecen and Sands, 1980).

Obviously, the use of heavy off-road equipment in the transportation and reconstruction of severely disturbed soil profiles can contribute to severe persistent soil compaction. The U.S. Bureau of Mines commissioned a study of different methods of reconstructing prime farmland soil in the midwestern United States (Albrecht, 1984). Three methods of replacing subsoil or rooting medium were investigated: scrapers, bucket-wheel excavator/spreading conveyor, and backdumping with trucks. In each method scrapers were used to deposit a layer of topsoil. All methods resulted in excessive subsoil compaction, which was caused by scraper traffic during topsoil deposition. Dunker et al.

(1991) have shown that when topsoil was deposited without traffic on subsoil, significantly high crop yields and significantly lower subsoil cone penetration strength resulted.

Powell et al. (1985) and Barnhisel et al. (1986) presented the results of research in Kentucky aimed at identifying preferable methods of prime farmland reconstruction. At the Peabody Coal Company River Queen mine near Central City, experimental plots were constructed to determine the effects of deep tillage or ripping and deep rooting crop species upon the amelioration of a silt loam prime farmland soil reconstructed by scraper placement and dozer grading. At the nearby Gibraltar mine, the effects of placement method and post-placement deep tillage on the physical properties and productive potential of two prime farmland soils were also examined.

This study presents the results of field determinations of subsoil bulk density in order to:

1. Determine the comparative effects of different species of vegetation, planted immediately following reconstruction, on amelioration of excessive subsoil compaction.
2. Determine the effect of deep tillage or ripping on reduction of subsoil bulk density.
3. Determine the effect of placement method on initial subsoil bulk density and on changes in bulk density over time.

EXPERIMENTAL METHODS

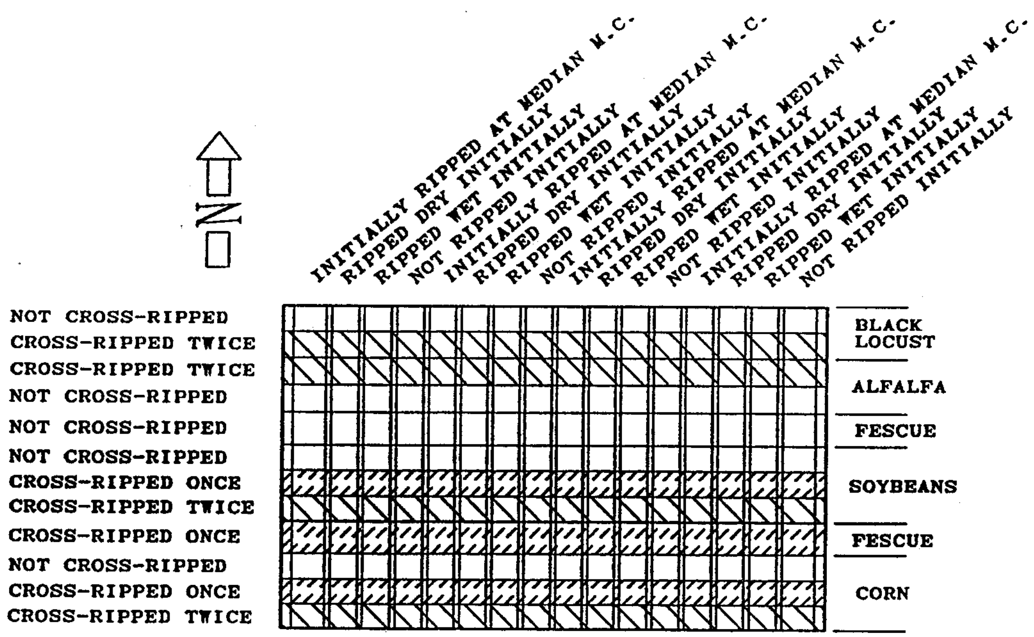
Experimental plots reconstructed using prime farmland soils at the River Queen and the Gibraltar surface mines of the Peabody Coal Company in northern Muhlenberg County, Kentucky as well as methods of measuring soil bulk density are described as follows.

River Queen Plots

An experimental soil profile was constructed during the fall of 1983 at the River Queen site from a disturbed Sadler (fine-silty, mixed, mesic, Glossic Fragiudalf) silt loam soil using scrapers and dozers. A mixed fine-silty subsoil (B horizon) material was deposited over graded spoil to an approximate depth of 80 cm (32 in.) in successive layers deposited by scrapers. Approximately 20 cm (8 in.) of low organic matter silt loam topsoil (A horizon) material was then deposited by scrapers and graded by wide-track dozers to minimize ground contact pressure.

A rectangular area 91 m x 145 m (300 ft x 475 ft) of reconstructed soil was established at the site (see Fig. 1). The area was divided into 16 plots, 7.6 m (25 ft) wide oriented N-S, separated by 1.5 m (5 ft) horizontal strips. Initial deep tillage treatments were then applied using a Rome ripper with parabolic shanks spaced 1.2 m (4 ft) apart to an approximate depth of 61 cm (24 in.). Soil

Figure 1. Diagram of experimental reconstructed prime farmland (Sadler Silt Loam) Soil at River Queen Mine showing vegetative and ripping treatments.



was ripped following reconstruction at three levels of moisture content: dry, 1/2 field capacity, and field capacity, with a non-ripped control. Each set of ripping treatments was replicated four times.

Various species of vegetation were superimposed on these experimental plots by subdividing the area in the E-W direction. Parallel strips or plots were established as follows from north to south (see Fig. 1): 15.2 m (50 ft), local black locust; 15.2 m (50 ft), alfalfa (Vernal variety); 9.1 m (30 ft), KY 31 tall fescue; 21.3 m (70 ft), no-till soybeans; 9.1 m (30 ft), KY 31 tall fescue; and 21.3 m (70 ft), no-till corn.

During 1985, the corn and soybean plots were disked and planted and two-thirds of each plot was ripped in the E-W direction. In 1986, the plots were disked and planted, then 1/3 of each plot was again ripped in the E-W direction. The plots planted in black locust, alfalfa and fescue were mowed in 1985 and 1986. In 1987, the black locust plot was disked to a depth of 15 cm (6 in.) and the alfalfa and tall fescue plots were treated with herbicide. Subareas of each plot were again ripped and the entire area was planted to no-till corn. During 1988-90, the area was planted in no-till corn, conventionally tilled corn and conventionally tilled grain sorghum, successively, with no additional ripping. Additional details concerning the experimentation associated with these plots is given by Powell et al. (1985).

Cylindrical soil cores (5 cm (2 in.) dia., 15 cm (6 in.) long) were collected from each ripping x crop plot area immediately after soil reconstruction (prior to any planting or ripping) in early 1984 using a Giddings hydraulic sampler. Initial bulk density was thus determined for each 15 cm (6 in.) layer of reconstructed soil. Additional core samples were collected in 1985 and 1986 in the corn plots and in 1987 in the alfalfa plots. In 1988, volumetric cores were collected and bulk density was also determined using a gamma ray attenuation gauge. The plots sampled in 1988 were: corn, never ripped; corn, initially ripped dry (N-S), cross-ripped (E-W) in 1985, 86 and 87; alfalfa, never ripped; and, black locust, never ripped. The corn, black locust and alfalfa plots were again sampled or measured in the fall of 1990 using a dual probe gamma density gauge and again in the fall of 1991 using volumetric cores.

Gibraltar Plots

Two soil profiles were reconstructed at the Gibraltar mine site using the previously described Sadler soil and a Belknap (coarse-silty, mixed, acid, mesic, Aeric Flavaquent) silt loam soil. Table 1 shows the horizon designations and depths for these two reconstructed soils.

Two methods were used to reconstruct the soils in the fall of 1982 and spring of 1983. Eight parallel strips, 21.3 m x 97.5 m (70 ft x 320 ft) were deposited of each soil using two equipment handling methods and using both direct placement and stockpiling (see Fig. 2). In the conventional method, 18.3 m^3 (24 cu. yd.) scrapers were used to deposit subsoil in successive layers or lifts of approximately 40 cm as needed. Grading was accomplished by dozers equipped with wide tread to reduce contact pressure. Approximately 20 cm (8 in.) of topsoil was deposited by scrapers and graded.

The other method involved the use of 32 m^3 (35 yd^3) end-dump trucks. The trucks deposited subsoil by horizon without driving on the plots. Grading of each horizon was done using wide track dozers. Topsoil was placed in identical fashion with final grading by dozers.

In the spring of 1983, alfalfa was planted at both ends of the area in 12.2 m (40 ft) strips, perpendicular to the main treatment plots. In the center, 12-row strips of corn and soybeans were alternated giving four replications. In the fall of 1984, one half of each main treatment strip was ripped to a depth of 61 cm (24 in.) at 1.2 m (4 ft) spacing, in the areas planted in corn and soybeans. Only corn was planted in the interior subplots in 1984 and 1985. In 1986, the entire area was planted in corn, including the end strips which had been in alfalfa for 4 years. During 1987-90, the entire area was planted in corn, soybean, wheat, and wheat, successively. Conventional tillage methods were used for seedbed preparation and row-crop cultivation as appropriate. Additional details concerning the experiment plot design at this site is given in Barnhisel et al. (1986).

A Giddings hydraulic sampler was used to extract volumetric bulk density cores from each of the soils prior to disturbance. Four replicated samples of 5.1 cm (2 in.) dia. x 15.2 cm (6 in.) cores were collected at depths of 0-15.2, 15.2-30.5, 45.7-61, and 76.2-91.4 cm (0-6, 6-12, 18-24 and 30-36 in.). Following construction of the plots, four replicated core samples were collected from each treatment strip at 15.2 cm (6 in.) depth increments to a depth of 91.4 cm (36 in.).

A dual-probe gamma ray density gauge was also used to measure in situ soil bulk density. In 1989, four replicated measurements were made in interior zone of the following treatment strips for both soil types: a)

Table 1. Horizon designation and depths of Sadler and Belknap soils (from Barnhisel et al., 1986).

Soil Series	Horizon	Depth from Surface (cm)
Sadler	Ap	0-18
Sadler	B2t, A'2	18-64
Belknap	Ap	0-20
Belknap	B21, B22g, B23g	20-90

direct scraper placement, never ripped; and, b) direct truck placement, never ripped. The measurement depths were 20.3 cm (8 in.), 50.8 cm (20 in.) and 61 cm (24 in.). In 1990, gamma density measurements were replicated 3 times for both soil types in the following treatment strips: a) direct scraper placement, never ripped; b) direct scraper placement, ripped; c) direct truck placement, never ripped; and, d) direct truck placement, ripped. Measurements were made at 5.1 cm (2 in.) depth increments to a depth of 91.4 cm (36 in.).

Soil moisture content was determined at each bulk density sampling location. When volumetric cores were used to determine soil bulk density (prior to 1989), soil moisture content was determined gravimetrically. In 1989, small samples were collected during the drilling of vertical access holes for the gamma density gauge. In 1990, soil moisture content was determined using a gauge which measured neutron scattering. This method has been shown reliable for measurement, below a depth of approximately 10 cm (Black et al., 1965).

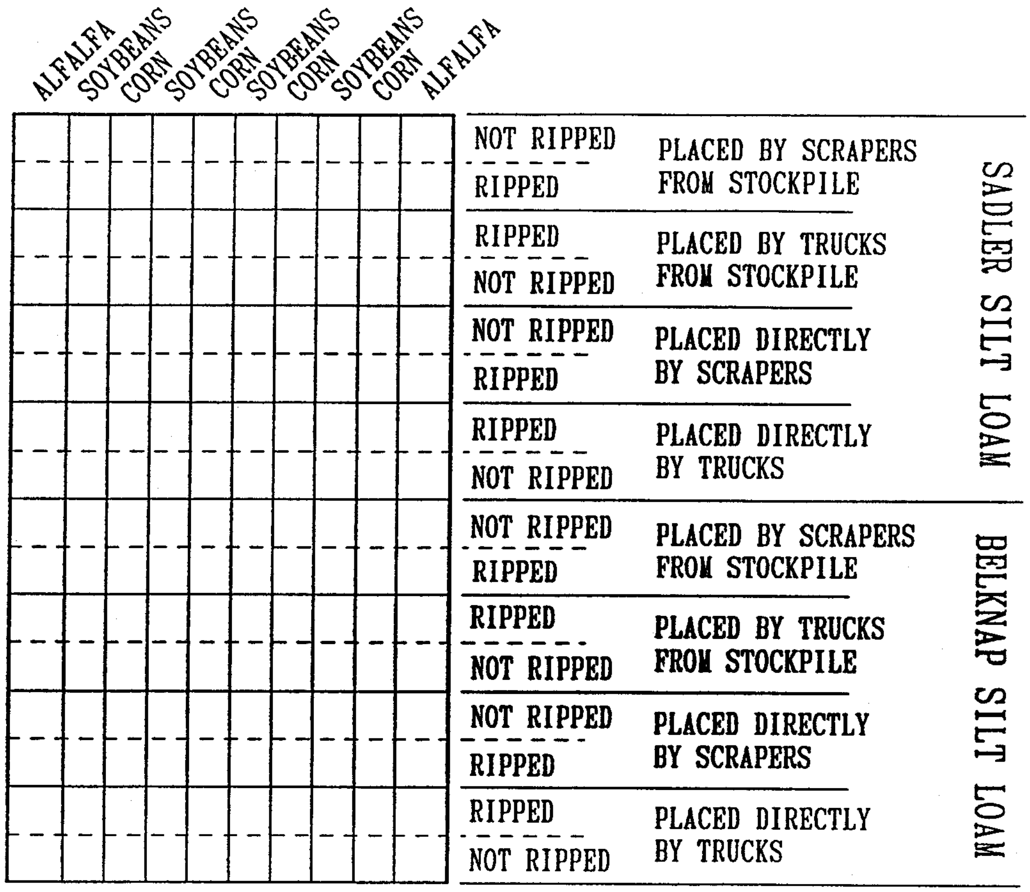
RESULTS AND DISCUSSION

River Queen Plots

Figures 3 and 4 present the results of the various determinations of subsoil bulk density versus depth at this site. Dry subsoil bulk density is plotted versus depth for each major treatment examined. Each profile represents the mean of four replicated measurements.

Comparison of subsoil bulk density versus depth profiles immediately after reconstruction indicates substantial compaction of this soil relative to its predisturbed state. Subsoil bulk density for the natural Sadler soil increased from approximately 1.43 Mg/m^3 at $z = 23$ cm (9 in.) to 1.63 Mg/m^3 at $z = 83.8$ cm (33 in.) (Powell et al., 1985). Subsoil bulk density following reconstruction was approximately 1.8 m^3/Mg for all plots below the depth of 38 cm (15 in.), except for the non-ripped plots planted in corn, which was approximately 1.7 Mg/m^3.

Figure 2. Diagram of experimental reconstructed prime farmland (Sadler and Belknap Silt Loam) soils at Gibraltar Mine showing placement and ripping treatments.



The corn plots which were never ripped exhibited gradual increase in subsoil density from reconstruction until 1988, followed by a notable decrease between 1988 and 1990. Measurements in 1991 were slightly higher than 1990, but confirm a slight decrease in bulk density over time. Only in 1988 was subsoil density as high as that in the corn plots which received the most ripping. The clear effect of all factors operating over time was to substantially decrease bulk density in the upper subsoil (40-60 cm), while having less effect on the deep subsoil (> 70 cm). It is not clear from these plots, however, that ripping affected a reduction in subsoil bulk density that would not have occurred by means of rooting actions or other natural phenomena.

The alfalfa and black locust plots were approximately equivalent in terms of deep subsoil bulk density from reconstruction to measurement in 1988. Higher subsoil bulk density in the black locust plots (for $z > 50$ cm) measured in 1988 probably resulted from the heavy disking used to destroy the black locust saplings in 1987.

Clearly, the notable reduction in subsoil bulk density in the black locust plots is the most intriguing result. An approximate reduction of 0.2 Mg/m^3 is indicated without the use of deep tillage. Additional field measurements will be made during the spring of 1992 to confirm this result. If the aggressive rooting behavior of black locust indeed created conditions whereby natural phenomena can further reduce subsoil bulk density, then this species could be an important consideration in prime farmland reclamation.

Figure 3. Soil bulk density profiles at various times in experimental plots, initially planted in corn, at the River Queen Mine.

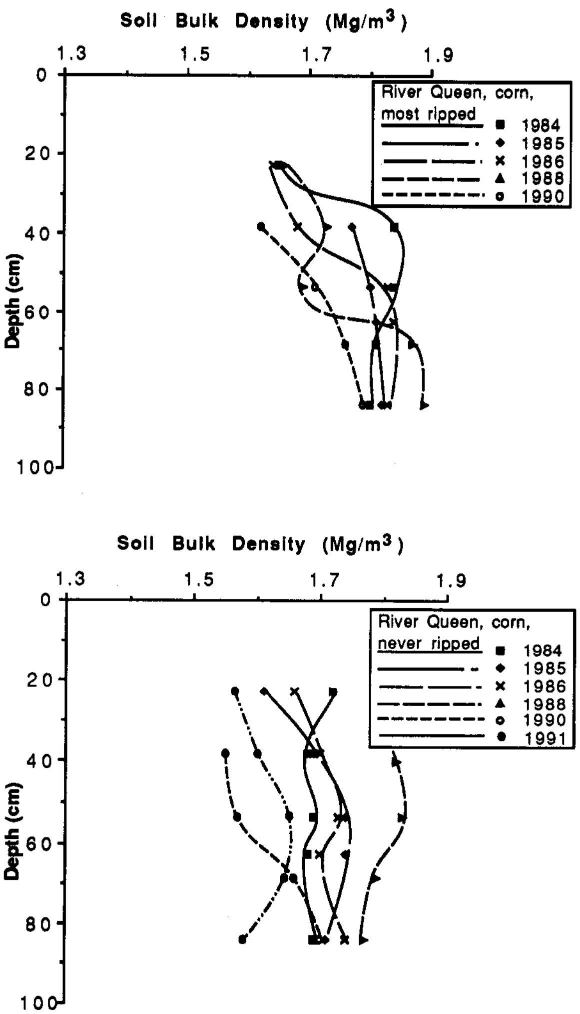
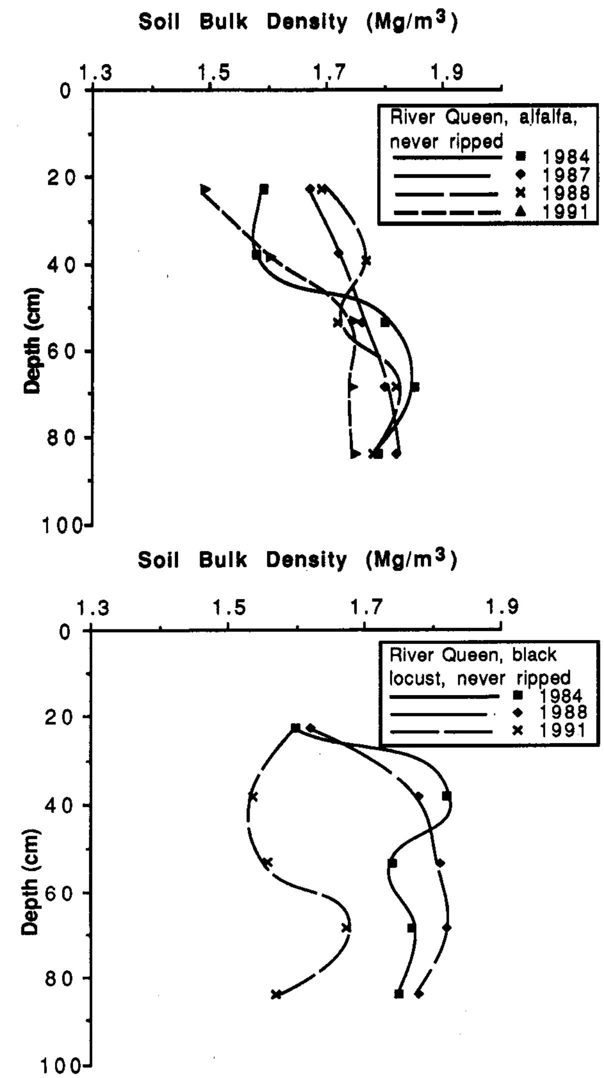


Figure 4. Soil bulk density profiles at various times in experimental plots, initially planted in alfalfa and black locust, at the River Queen Mine.



Gibraltar Plots

Figures 5 and 6 present the results of the various subsoil bulk density versus depth profiles measured at this site. The bulk density immediately after reconstruction was substantially greater than in the pre-mined state at all depths for both soil types and placement methods. Further, there is no clear indication, in either soil type, that placement method significantly affected bulk density immediately after reconstruction. This was somewhat surprising since only dozer traffic was applied to the plots constructed by truck placement. The results would indicate that for these soils and the conditions which prevailed at the time of placement, dozer traffic compacted subsoil as much as scraper/dozer traffic.

Bulk density measurements taken in 1989 in non-ripped plots indicate that subsoil bulk density increased for $z \geq 50$ cm (20 in.) and decreased for $z < 50$ cm. The exception to this was the truck-placed Belknap soil, where subsoil bulk density decreased at all depths, compared with the initial (1983) profile.

The 1990 measurements present contrasting behavior in the two soil types. In the Sadler soil, subsoil bulk density apparently decreased relative to the 1983 and 1989 measurements in both ripped and non-ripped plots. In the Belknap soil, however, subsoil density increased in the non-ripped plots compared to earlier measurements. Ripping appeared to decrease subsoil bulk density in both soils for both placement methods.

Table 2 presents a comparison of mean bulk densities measured in 1990 for the various experimental treatments, i.e. placement method and ripping, using Duncan's New Multiple Range Test (SAS, 1986). In the Sadler soil, ripping resulted in significantly lower bulk density (5% level) at the 61-76.2 cm (24-30 in.) depth in the truck-placed plots, whereas there was no significant reduction at any depth in scraper-placed plots. In the Belknap soil, ripping produced significantly lower bulk

Figure 5. Soil bulk density profiles at various times in experimental plots, reconstructed by two methods, in Sadler Silt Loam Soil at the Gibraltar Mine.

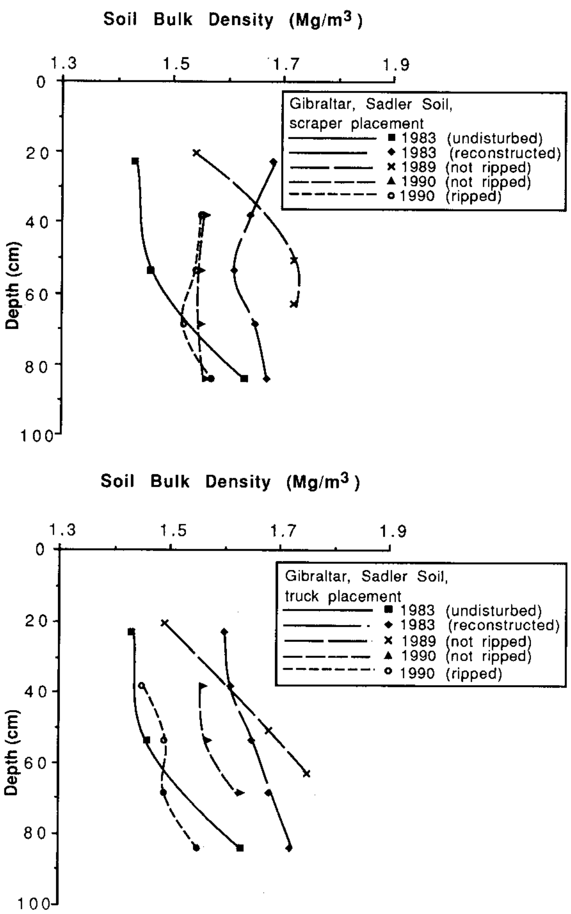
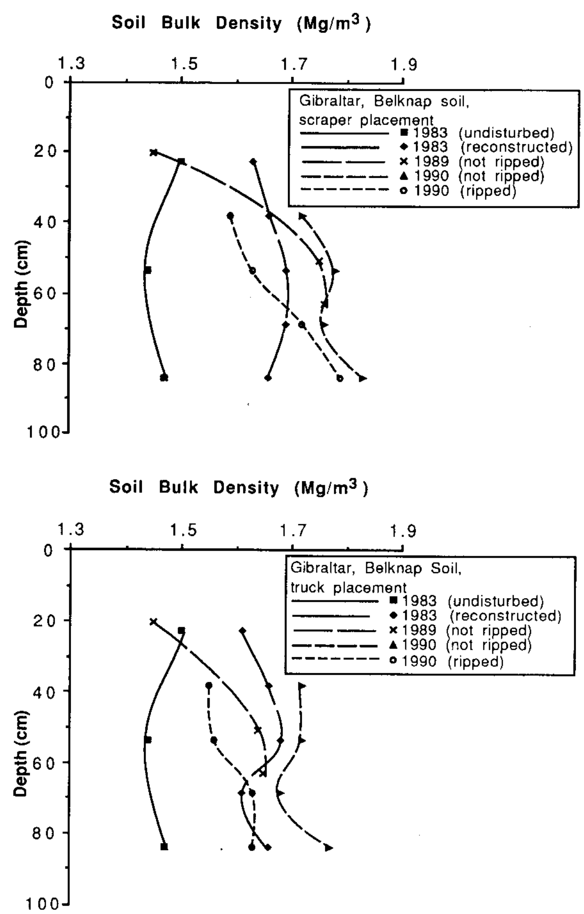


Figure 6. Soil bulk density profiles at various times in experimental plots, reconstructed by two methods, in Belknap Silt Loam Soil at the Gibraltar Mine.



density within all subsoil depths except 61-76.2 cm (24-30 in.) in the truck-placed plots, while reducing density only in the upper subsoil (30.5-61 cm (6-18 in.)) in scraper-placed plots. Significantly lower bulk density for truck placement was indicated only in the Belknap soil at the 76.2-91.4 cm (30-36 in.) depth in plots which were ripped.

In the Sadler soil, subsoil bulk densities measured in 1990 seem to be approaching that of the premining condition in all plots subjected to ripping. In the Belknap soil, however, subsoil bulk density remains substantially higher than that of the premining condition for all cases. In this soil, ripping substantially reduced subsoil bulk density, yet was unable to approach pre-disturbance levels.

CONCLUSIONS

The conclusions of the study are as follows:

1. Primary planting of a reconstructed prime farmland soil in alfalfa for three growing seasons resulted in a slight decrease in subsoil bulk density measured six years after reconstruction, whereas planting in black locust for the same time period produced a substantial reduction. Additional measurements will be taken in 1992 to confirm this result.
2. In all cases examined, ripped plots exhibited lower subsoil bulk density than non-ripped plots.
3. There was no significant difference between the truck and scraper placement methods with regard to subsoil bulk density.

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Table 2. The effect of placement method and deep tillage on subsoil bulk densities of two reconstructed prime farmland soils by Duncan's New Multiple Range Test

Depth (cm)	Truck Placement Not Ripped	Truck Placement Ripped (610 mm)	Scraper Placement Not Ripped	Scraper Placement Ripped (610 mm)
Sadler Silt Loam				
30.5-45.7	1.56a*	1.45a	1.56a	1.55a
45.7-61	1.57a	1.49a	1.55a	1.54a
61-76.2	1.63a	1.49a	1.55ab	1.52ab
76.2-91.4	—	1.55a	1.56a	1.57a
Belnap Silt Loam				
30.5-45.7	1.72a	1.55b	1.72a	1.59b
45.7-61	1.72ab	1.56c	1.78a	1.63bc
61-76.2	1.68ab	1.63b	1.76a	1.72ab
76.2-91.4	1.77a	1.63b	1.83a	1.79a

*At a given depth, mean bulk densities designated by the same letter are not different at the 5% level of significance.

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A Soil-based Productivity Index to Assess Surface Mine Reclamation

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Abstract. Need exists for a method to evaluate surface mine reclamation in the absence of test plots. Differential distribution of rainfall by summer thunderstorms, pests, soil variability, differential variety performance, and frequent problems with timing of spring planting all contribute to the difficulties of comparing yields among reclaimed and unmined sites. A soil-based productivity index developed at the University of Missouri-Columbia may provide a conceptual framework useful for developing a productivity index suitable for reclaimed minesoils. The concept of the productivity index is that the soil environment affects root growth, and that plant yield will be proportional to root growth. Five easily measured soil properties — aeration, pH, bulk density, potential available water-holding capacity, and salinity — were chosen to represent the soil environment. An equation was developed which uses sufficiencies of individual soil properties based upon optimum conditions in an ideal soil. A productivity index of 1.0 represents a soil with no rooting restrictions. The productivity index was designed to allow region- and species-specific modification. Examples of such modifications are presented. Additional research needed to futher refine the productivity index is discussed.

INTRODUCTION

Evaluating reclamation is costly and time-consuming. Law requires that for bond to be met, crop production on reclaimed minesoils must equal or exceed crop production on similar unmined soil. The comparison requires test plots on reclaimed and unmined soil. Need exists for a way to assess reclamation in the absence of test plots. A soil-based productivity index is discussed which appears to be a suitable method to evaluate surface mine reclamation. The productivity index is based upon the premise that root growth will be a function of the sufficiency of the soil as a rooting medium and that plant growth and yield will be proportional to root growth. This paper will discuss the rationale and justification for modifying a soil-based productivity index (PI) for use as a means to assess surface mine reclamation. The format will be to: 1) justify the need for a soil-based PI; 2) present the conceptual framework for a PI developed in Missouri; 3) discuss weaknesses of the PI as it relates to surface mine reclamation.

Numerous region-specific soil and overburden characteristics have been shown to affect plant root growth in reclaimed minesoils. In the northern Great Plains, overburden materials are often saline or sodic (Halvorson et al., 1980) If smectite is common in the clay fraction of sodic soils, clay dispersion reduces water infiltration and root penetration, which reduces plant yield (Doll et al., 1984). Migration of salts from the subsoil into the surface soil frequently reduces the rooting volume and causes accompanying declines in productivity (Halverson et al., 1980).

In western Kentucky, forage yields on surface mine spoils were limited by low water-supplying capacity and low available P. Plants were rendered draught-susceptible because the acid spoils restricted root growth (Barnhisel, 1977). Minesoils in West Virginia were characterized by acidity, stoniness, high bulk density, low porosity, and low water retention capacity. Reclamation of these soils is compounded by the acidic nature of the subsoils of unmined soils and by steep slopes (Thurman and Sencindiver, 1986). Minesoils in the Missouri glacial till landscapes are characterized by high bulk density, high contents of 2:1 clays, and low available P (Hanson et al., 1984).

Power et al. (1978) reported that texture, structure, exchangeable Na content, bulk density, compaction and the degree and length of slope — individually and in combination — control infiltration, runoff, and evaporation from reclaimed soils. McFee et al. (1981) found that water storage capacity and electrical conductivity were most frequently the properties causing plant growth responses on reclaimed soils. Minesoils generally have higher bulk density, lower porosity, lower permeability, higher coarse fragment content and lower available water-holding capacity than unmined soils (Brussler et al., 1984; Indorante et al., 1981), and these properties

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are affected by reclamation techniques (Schafer et al., 1980). Reclamation techniques also affect structure of minesoils, and thereby affect plant rooting patterns (McSweeney and Jansen, 1984).

Increasing depths of replaced topsoil — to certain minimum thicknesses which apparently vary with topsoil and subsoil properties, climate and crop characteristics — repeatedly have been shown to be positively correlated with crop yield (Halvorson et al., 1980; Power et al., 1981). Reduced hydraulic conductivity in replaced topsoil materials can reduce forage production, even when nutrient levels are adequate (Merrill et al., 1985). Quality of replaced topsoil in the northern great plains often affects forage quality, which, in turn, affects livestock performance (Schuman and Power, 1981). Wheat, barley, and corn yields were not increased by additions of N and P fertilizer on replaced non-saline, non-sodic topsoil (Halverson et al., 1986). Topsoil quality in reclaimed lands is a function of the chemical and physical properties of the unmined topsoil and of the reclamation procedures.

Optimum topsoil thickness for crop productivity on reclaimed minesoils is also a function of replaced subsoil properties, including chemical and physical characteristics and thickness (Doll et al., 1984; Fehrenbacher et al., 1982). Physical properties related to porosity and available water-holding capacities appear to be most important, and these are affected by reclamation techniques (Doll et al., 1984; Fehrenbacher et al., 1982). All of the reclamation problems listed above seem to be quantifiable in terms of the productivity index.

Public Law 95-87, mandated in 1977, has required that reclamation of minesoils be established by comparing crop yields from reclaimed soils with yields from similar, unmined soils. Limitations to this approach are many. Crop varieties suitable for unmined soils may perform differently on reclaimed soils. Crop test plots in reclaimed minesoils areas may attract rodents, pests, and diseases out of proportion to plot sizes. Magnitudes and patterns of soil variability probably will differ between unmined and reclaimed minesoils (Schroer, 1978), making yield comparisons between them difficult. Summer precipitation patterns can vary greatly over short distances, particularly in the continental interior, and the timing of precipitation during the growing season may profoundly affect crop yields (Thompson et al., 1991). Finally, establishing and maintaining crop test plots may involve serious logistical and management and fiscal problems for mine operators who often do not have the equipment or trained personnel for farming tasks.

Doll et al. (1984) and Wollenhaupt (1985) investigated soil-water characteristics in minesoils and reviewed results of years of studies of reclamation practices. They concluded that reclamation success could and should be evaluated by relating crop yields to properties of the reclaimed soils. Wollenhaupt (1985) investigated the suitability of an existing productivity index (PI) developed by Scrivner and coworkers (Kiniry et al., 1983) for minesoil evaluation and concluded that the PI possessed the following benefits:

1. It eliminates problems accompanying the use of reference areas, such as accounting for climate variability and management practices.
2. It can be used to design the best possible constructed soil profiles using available soil materials.
3. Soil conditions created during reclamation can be readily and quickly assessed and existing problems can be identified and corrected.
4. It could be used to justify partial or complete bond release.

THE SOIL-BASED PRODUCTIVITY INDEX

The concept of an index for assessing soil productivity is not new. Storie (1933) and Simonson and Englehorn (1938) attempted numerical rating of soil productivity. Huddleston (1984) and Henderson et al. (1990) reviewed the history and applications of productivity ratings. Huddleston's review is most applicable to agricultural soils. Henderson et al. focused upon the application of the Kiniry et al. (1983) PI for commercial forestry. The Kiniry et al. bulletin is out of print. Therefore, this manuscript will examine the conceptual framework of the Kiniry et al. (1983) PI in some detail.

The PI developed by Scrivner and his cooperators uses estimates of root distribution in the "ideal" soil. Root distribution was based upon water depletion studies (Horn, 1971) in an oak-maple forest on a Menfro silt loam (fine-silty, mixed, mesic Typic Hapludalf) on deep loess near Columbia, Missouri. Neill's (1979) thesis contains the literature review upon which was based the sufficiency factors for soil properties important to root growth. The Kiniry et al. (1983) bulletin (Neill is Kiniry's maiden name) is the culmination of the overall effort.

The fundamental concept of the PI is that root growth will be determined by the soil environment (soil properties), and plant yield will be proportional to root growth (Figure 1). Effects of climate, plant genetics, and management were "considered to be describable in terms of yield response. Thus, they could be combined with the soil parameters in a more complete prediction of yield" (Kiniry et al., 1983). Management affects yield directly, by controlling competition and disease, etc., and indirectly by affecting soil physical and chemical properties. The conceptual PI assumes optimum management. Plant nutrient requirements were omitted because the elements, being mobile within the soil-plant system, are replenishable.

Neill (1979) identified five soil properties — potential available water storage capacity (PAWC), bulk density, soil pH, salinity (electrical conductivity(EC)), and aeration — as being easily measured soil parameters shown to influence plant root growth. The emphasis of the literature search was upon those soil properties identified to be important to growth of corn (*Zea mays* L.) and soybean (*Glycene max* (L.) Merr.) roots. Subsequent field quantification of the PI model resulted in loss of precision when aeration was included. Kiniry et al. (1983) attributed the inadequacy of the aeration factor to the dynamics of the time-depth distribution of soil areation. The complexity of this dynamic component of the soil system demands additional, long-term research.

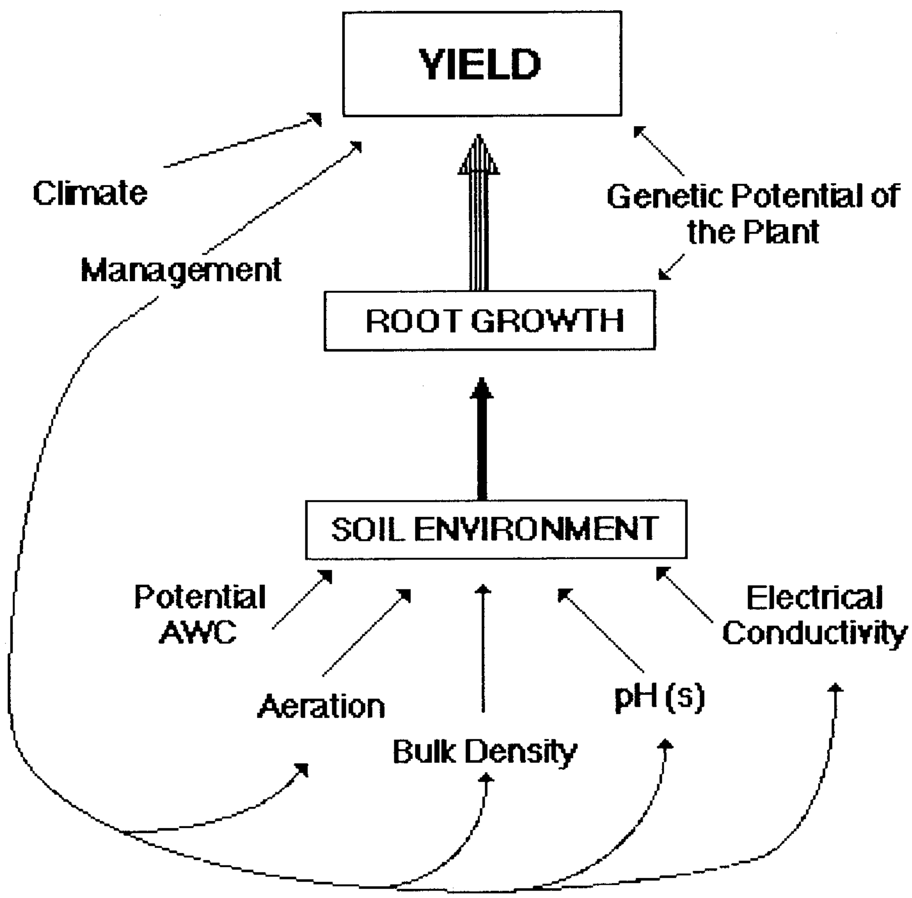
Root distribution in the "ideal" soil

The Menfro soil was chosen as the ideal soil because it contained no known physical or chemical impediments to root growth, and was occupied by deep-rooted perennial species — primarily sugar maple (*Acer saccharum*) and bitternut hickory (*Carya cordiformis*). The observed rooting depth during Horn's (1971) study was 356 cm. The inverse hyperbolic sine function which describes root distribution was developed from measurements of water depletion. Horn used the term "RI" to describe the fractional distribution of roots in 10 cm soil increments. The total of RI's is 1.00 because the RI is the decimal fraction of all roots in the profile. Kiniry et al. (1983) developed RI values for possible rooting depths of 100 cm and 200 cm (Figure 2). Kiniry et al. cautioned that the choice of rooting depth will affect the RI values for any increment of the soil profile. Greater rooting depth diminishes the importance of any individual RI increment because it represents a smaller portion of the whole.

Scrivner reported the RI as a 10 cm depth increment to accommodate those persons not trained to recognize genetic soil horizons (C.L. Scrivner, personal communication). Soil scientists could use soil horizons as the sampling unit rather than 10 cm increments, and could determine RI values for individual horizons.

Yield prediction precision with the PI would probably be enhanced with the development of species-specific "ideal" root distribution patterns. Gale and

Figure 1. Conceptual framework of the Productivity Index. (From Kiniry et al, 1983).



Grigal (1987) reported differing root distributions among tree species in northern hardwood forests. Proportional root distribution by depth was a function of total rooting depth, successional status (species), and tree age.

Boudeman (1989) used the PI to attempt to predict yield of Korean lespedeza (*Lespedeza stipulacea*), red clover (*Trifolium pratens* L.), and alfalfa (*Medicago sativa* L.). He found that root distribution varied annually. Higher proportions of roots were in the surface 20 cm of the soil in 1987 (a relatively "moist" year) than in 1988 (a drought year). Additionally, root distribution varied with landscape position across a summit, shoulder, backslope, and footslope — probably as a result of lateral soil water movement. Boudeman reported that root distribution differed according to time and frequency of forage harvest.

Additionally, Boudeman (1989) observed that water depletion under the forage legumes was in a different pattern than observed by Horn (1971). In Boudeman's study, legumes first withdrew soil water from the surface, then progressively withdrew water from depth. Horn (1971) reported continuous water depletion throughout the profile, but with lesser amounts being taken with increasing depth increments. Boudeman suggested that the "ideal" root distribution Neill developed from Horn's work would have assumed a different appearance had it been based upon water extraction patterns of forage legumes.

Sufficiency factors

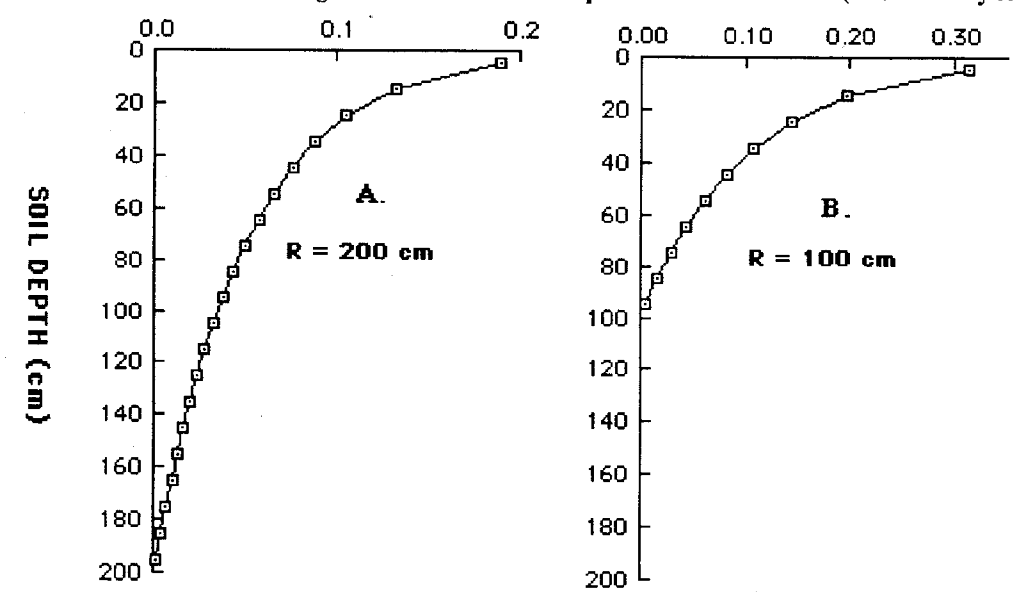
Each of the measured soil properties in the model requires a root growth response function. The response function is described as its "sufficiency" in comparison to a soil property which does not inhibit root growth. The ideal soil property would have a sufficiency of 1.0, and a soil property which permitted no root growth would have a sufficiency of 0.0. A sufficiency value of 0.50 indicates that root growth is potentially 50% of expected growth under unrestricted conditions.

Studies have shown that root growth is inversely proportional to soil strength measured as resistance to penetration. (Blanchar et al., 1978). Scrivner selected bulk density as an easily measured indication of soil strength. Soil strength is a function of soil texture, soil moisture at time of sampling, and soil structure (Towner, 1974; Pearson, 1966), so care must be taken in obtaining bulk density values. Method of sampling greatly affects the bulk density measurement. Indorante (1990) used the saran-clod method of bulk density determination in a Menfro at the site of Horn's (1971) work, and obtained lower sufficiency values than Neill (1979). Indorante's sampling method had eliminated interstitial voids between primary soil aggregates (prisms), giving him a higher bulk density measurement.

The bulk density sufficiency relationship (Figure 3) reveals that bulk densities less than 1.3 do not limit root growth. Between values of 1.3 and 1.55 root growth gradually declines. Above values of 1.55, root growth is rapidly diminished. Above values of 1.8, root growth is severely limited.

The interactions among soil structure and root growth require additional investigation. Hammer (1986) and Indorante (1990) observed forest tree roots growing on block and prism faces in subsoils. Conway-Nelson (1991) reported roots of native prairie species following joints in weathered sandstone and shale below the soil solum. In strongly structured soils, bulk density alone

Figure 2. Predicted fractions of root growth in ideal soils at depths of 100 and 200 cm. (From Kiniry et al., 1983).



may not be a precise estimate of root growth potential. In minesoils, McSweeney and Jansen (1984) observed profuse root growth with strongly structured material. In massive, reclaimed subsoils, the only roots were along desiccation cracks and often were flattened and compressed.

Soil pH is highly correlated with other soil chemical parameters, and was selected as the single, easily-measured soil parameter most representative of the soil chemical environment. However, soil pH is a dynamic component which varies temporarily and spatially with salt concentration of the soil solution, soil moisture, soil atmospheric conditions, and status of organic matter decomposition (Russell, 1973; Hammer et al., 1987; Peterson and Hammer, 1986). Rhizosphere studies using microelectrodes (Conkling and Blanchar, 1988) have shown that pH at the soil-root interface may not be the same as pH of the bulk soil solution. Soil pH measured in $CaCl_2$ will be a pH measurement less affected by soil solution rations than soil in water (Schofield and Taylor, 1955).

Figure 4 shows the sufficiency of pH. The threshhold pH for unlimited root growth is 5.5. The dotted line in Figure 4 represents an extrapolation performed by Kiniry et al. (1983) made in the absence of measured relationships. Development of root growth parameters is important in strongly structured acid soils, where ped faces may exhibit a different soil chemical environment than the bulk soil (Conway-Nelson, 1991). Additionally, some plants are known to be more tolerant than others of extremes in soil reaction. Species-specific work will be necessary to develop pH sufficiencies for agronomic crops.

Osmotic potential influences root growth in many regions, particularly semi-arid and arid environments in which salts are not leached from the soil profile by annual pulses of soil water. Electrical conductivity was chosen as a sufficiency factor in the PI because it is an

Figure 3. Sufficiency of bulk density (From Kiniry et al., 1983).

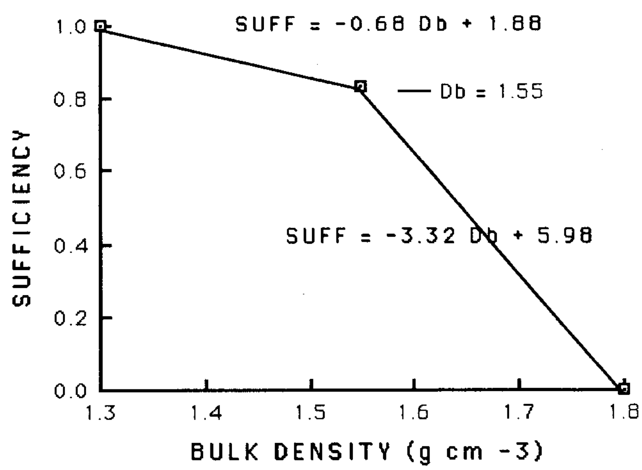
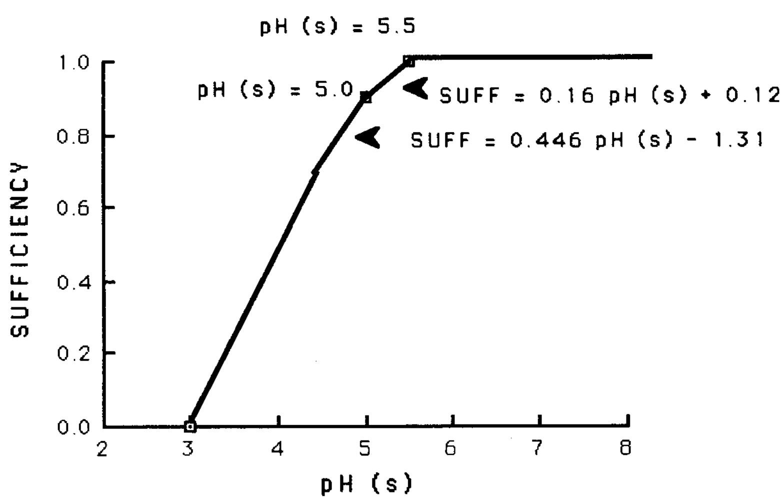


Figure 4. The sufficiency for pH(s) (from Kiniry et al., 1983).



easily measured parameter highly correlated with osmotic potential. In humid regions, EC can be eliminated from the PI equation.

The sufficiency relationship for EC is shown in Figure 5. This sufficiency factor was developed from work by Wadleigh et al. (1947) as modified by Richards (1969). Even in humid regions, some overburden materials used in surface mine reclamation contain salt concentrations and could necessitate the inclusion of the EC in a PI used to assess surface mine reclamation.

Potential available water storage capacity is the ability of the soil to supply water to plants in the absence of rainfall. The PAWC of a soil is influenced by texture, structure, and organic matter content. Unfortunately, PAWC is a static measure. It does not consider position in the landscape and the contribution of lateral subsurface water movement. This problem subsequently will be discussed in more detail.

The sufficiency of PAWC (Figure 6) is a linear relationship with a value of 1.0 when storage of soil water is 0.20 cm or greater cm^{-1} of soil depth. If soils contain rock fragments, a reduction in the sufficiency value is necessary. The reduction should be proportional to the volume of soil increment occupied by rock fragments. Silt and silt loam soils devoid of coarse fragments will have sufficiency of 1.0. It is likely that species-specific adjustments are necessary for this sufficiency factor.

The PI formula

The PI is calculated by measuring, for each soil depth increment or horizon, the soil properties upon which the sufficiencies are based. The soil property is converted to a sufficiency factor. Each depth increment is weighted by the RI factor for that increment in the ideal soil. The original productivity index was:

$$PI = \sum_{i=1}^{r} (RI \times A \times B \times C \times \ldots)_i \quad [1]$$

Figure 5. Sufficiency of electrical conductivity (From Kiniry et al., 1983).

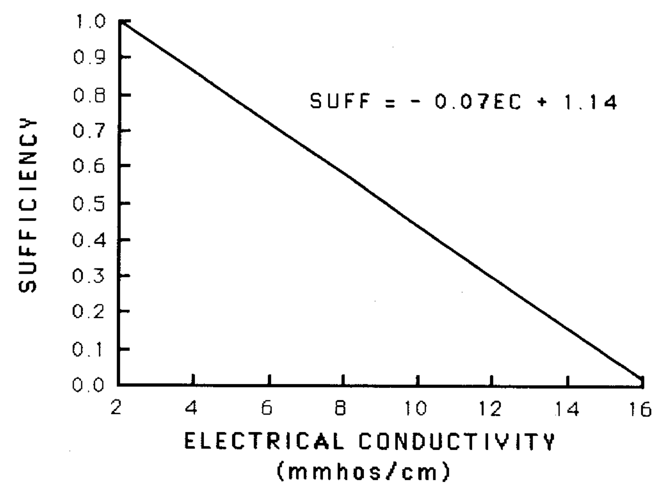
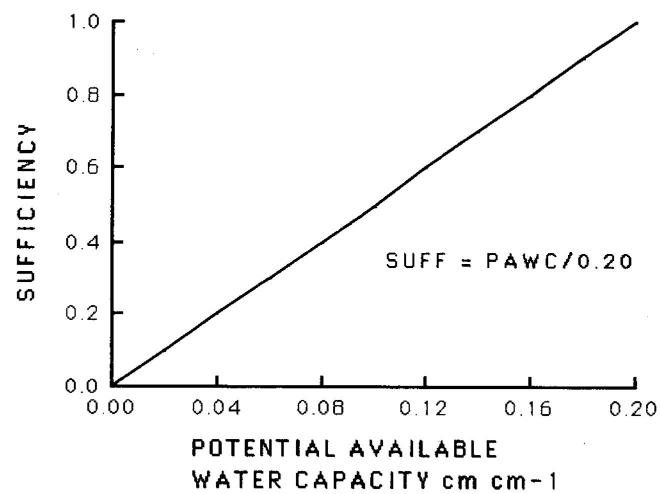


Figure 6. Sufficiency of potential available water capacity (From Kiniry et al., 1983).



where PI = the productivity index, RI = predicted root fraction in the ideal soil, and A through C = sufficiency factors for soil parameters 1 through 3, respectively, r = the total number of depth increments in the rooting profile, and i = the depth increment number (i = 1.2,3, .. r).

The PI formula can be modified for species-specific situations. Gale et al. (1992) modified the PI to develop RI values for soil horizons under white spruce (*Picea glauca* (Moench) Voss) plantations. The soil horizon-based PI was a better predictor of white spruce growth than the PI based upon incremental soil depth.

THE FLEXIBILITY OF THE PRODUCTIVITY INDEX

Scrivner (C.L. Scrivner, personal communication) predicted that the most important contribution of the PI would be its use as a conceptual framework from which to approach the interactions of plant roots with their soil environment. Those who have used the PI with this perspective have found it useful.

Camacho (1991) used a large soil data base in conjunction with growth data of leucaena (*Leucaena leucocephala*) and a massive literature review to develop a leucaena-specific PI for Central America. Camacho developed leucaena-specific sufficiency indices for soil pH, bulk density, and water-holding capacity. He reported that the soil pH sufficiency alone explained between 15 and 30% of variation in leucaena growth.

Leucaena habitat encompasses a broad ecological amplitude. Leucaena occupies sites whose conditions range from water-saturated for prolonged periods to extensive drought, when the tree drops its leaves. Camacho used the Thornthwaite water balance model (Thorthwaite and Mather, 1955) to develop an aridity index (AI) and a moisture index (MI) to account for climatic conditions during dry and wet periods. Sufficiency relationships were developed from each index. The PI developed from these sufficiency relationships explained from 25 to 99% of variance in leucaena yield in stands throughout Central America.

In addition to the previously mentioned refinement of equation [1], Gale et al. (1991) also developed species-specific sufficiency factors for the PI and used species-specific vertical root distributions developed by Gale and Grigal (1987). Gale et al. (1991) produced a sufficiency curve for depth to mottling to serve as the aeration sufficiency for white spruce, which occupies a wide range of soil drainage classes. They used texture-specific bulk density sufficiencies from Pierce et al. (1984). A sufficiency for topography was developed for white spruce, and, like Camacho (1991), they developed an index of aridity to account for climatic conditions. Gale et al. (1991) found the PI, as they modified it, to be a more precise predictor of white spruce growth in both young and old stands than site index. They recommended that sufficiency factors for nutrient requirements and stand age would further improve the PI.

Gantzer and McCarty (1987) used the unmodified Kiniry et al. (1983) PI to predict corn yield on a soil with varying thicknesses of topsoil and varying depths to a claypan. They found that 50% of the variation in PI was related to depth of topsoil and 62% was related to depth to clay. The PI was a better predictor of plant yield than topsoil or depth to clay. Regression analysis of yield on PI explained between 63 and 72% of the variation of yield within years. However, when a weather variable estimating total water use in July and August was used in conjunction with the PI, 82% of yield variance was explained.

CLIMATE AND SOIL WATER

One of the greatest challenges facing PI users is in addressing the dynamic nature of soil water and precipitation. The previous discussion indicated that some users have added climatic sufficiency factors to modified PI's to account for some of the yield variance produced by climatic and soil water conditions. The following discussion will clarify the need for more research in that arena.

Thompson et al. (in press) used the PI to evaluate corn growth on the same set of plots for five years. Their research indicates that climatic variance produces large yield differences among years. Figure 7 reveals a nearly three fold (3.1 to 8.2 kg ha^{-1}) yield difference on plots with a PI of 0.34 and receiving no irrigation. Similar yield differences were noticed within other PI values, but the range seems to decline with increasing PI value. The problem is complex. Irrigated corn plots exhibited greater yields than plots receiving water only through rainfall (Figure 8). The PI explained a smaller percentage of variance in the mean yield for five years in in irrigated than in rain-fed plots (Figure 9). A second order polynomial explained 68% of the yield variance in rain-fed plots (Figure 9A), but only 44% of the variance was explained in irrigated plots (Figure 9B). All irrigation was concurrent. The reduction in explained variance on irrigated plots seems to indicate that the plants were at different stages of development (and therefore of ability to use soil water) on plots with different soils and PI's. Soils with different PI values might require different management practices for the same crop species.

The soil landscape will affect the temporal distribution of soil water. Henderson et al. (1990) addressed this problem, and referred to the water-supplying capacity of different geomorphic elements within watersheds. The PAWC sufficiency in the PI is a static measure incapable of accounting for the lateral subsurface distribution of water in a landscape. Data from Conway-Nelson (1991) show that when rainfall is relatively uniformly distributed on a native prairie during a growing season, the effects of landscape position are mitigated. For example, Figure 10 indicates little yield difference as a function of landscape position in the Taberville Prairie in 1990. However, in 1989, a drought year, landscape position profoundly affected yields in the prairie (Figure 11). The lower headslope, a concave position receiving subsurface water from a large surrounding area, had the highest yield which exceeded by a factor of three the yield in the upper headslope. Figure 11 contains three transects — a headslope transect, a backslope transect, and a transect across a convex finger ridge. In all three transects, yield increased downslope with increasing ability of the surrounding landscape to supply water to those lower positions. That the yield differences are a function of soil water can be further substantiated by Figure 12, which shows the temporal distribution of soil water in the surface horizons of the summit, noseslope, upper finger ridge and headslope. The higher resistance readings indicate lower soil water. The headslope had the lowest resistance readings among those represented. The figure also reveals the dynamic temporal characteristic of soil water. Until the temporal attributes of soil water can somehow be addressed, much of the annual variance in crop yield will result from the differential accumulation of water across the landscape.

Figure 7. Corn yield as a function of the productivity index for a five year period on rainfed plots near Columbia, Missouri (From Thompson et al., (in press)).

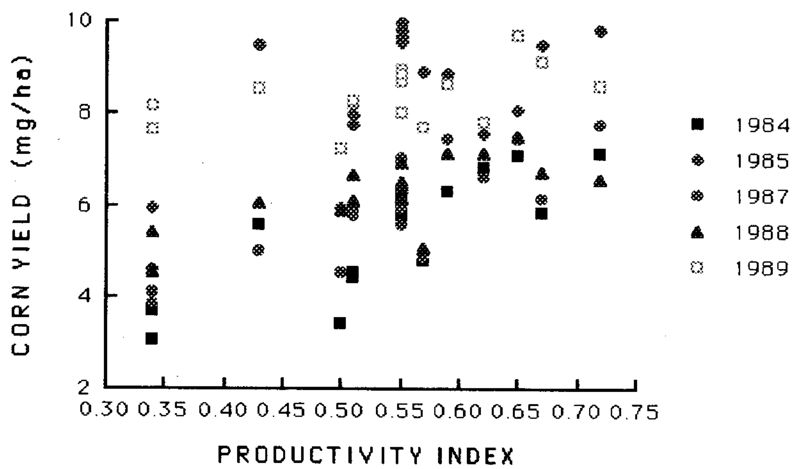
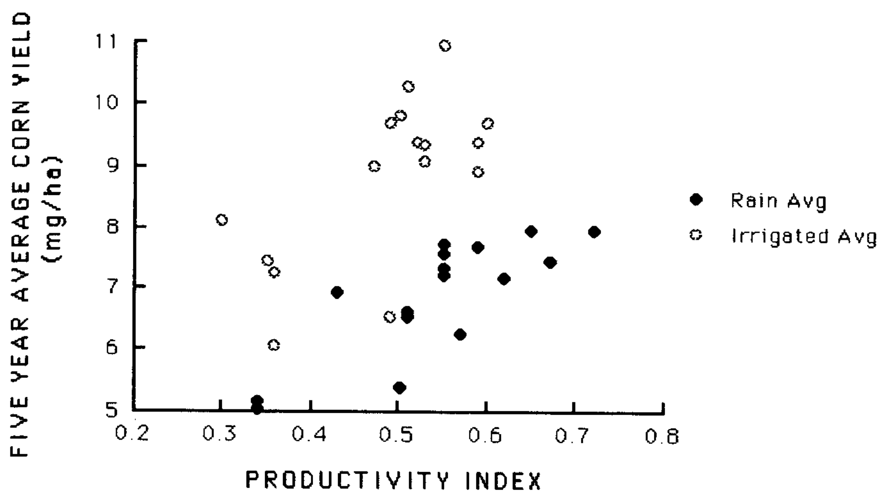


Figure 8. Five year average yield of rainfed and irrigated corn plots near Columbia, Missouri (from Thompson et al. (in press)).



CONCLUSIONS

The PI has been demonstrated to be an important method to quantitatively compare the potential productive capacities of different soils. It provides a conceptual framework from which researchers can approach region-, species-, and site-specific problems related to plant yield. The PI requires refinement for species-specific rooting distribution under "ideal" conditions. Region- or species-specific sufficiencies in addition to or different than those proposed by Kiniry et al. (1983) will probably be needed. The dynamic nature of the plant-soil-water continuum requires additional attention before the PI can be widely applied. However, the PI concept provides a focal point for researchers, and requires that the cause-and-effect relationships among plants and their environment be more closely examined that has been done in the past.

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Figure 9. Five year average corn yields for rainfed (A) and irregated (B) plots near Columbia, Missouri (from Thompson et al. (in press)).

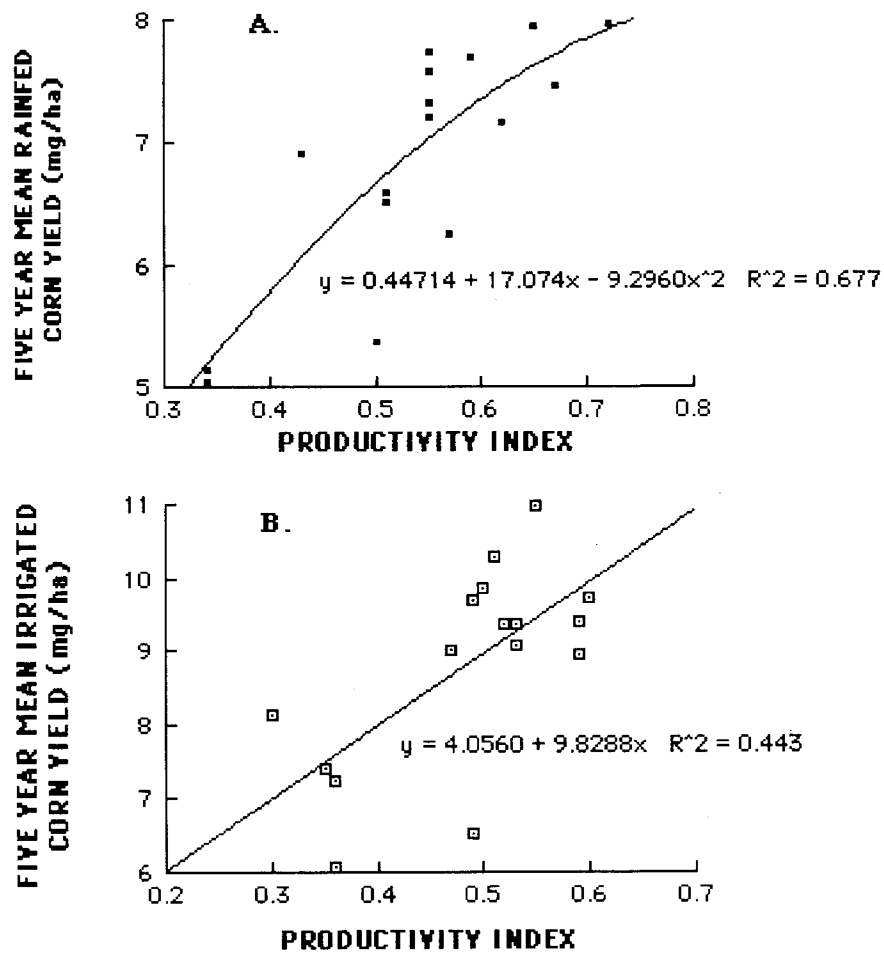

Figure 10. Total 1990 forage yield on Taberville Prairie, Missouri (from Conway-Nelson, 1991).

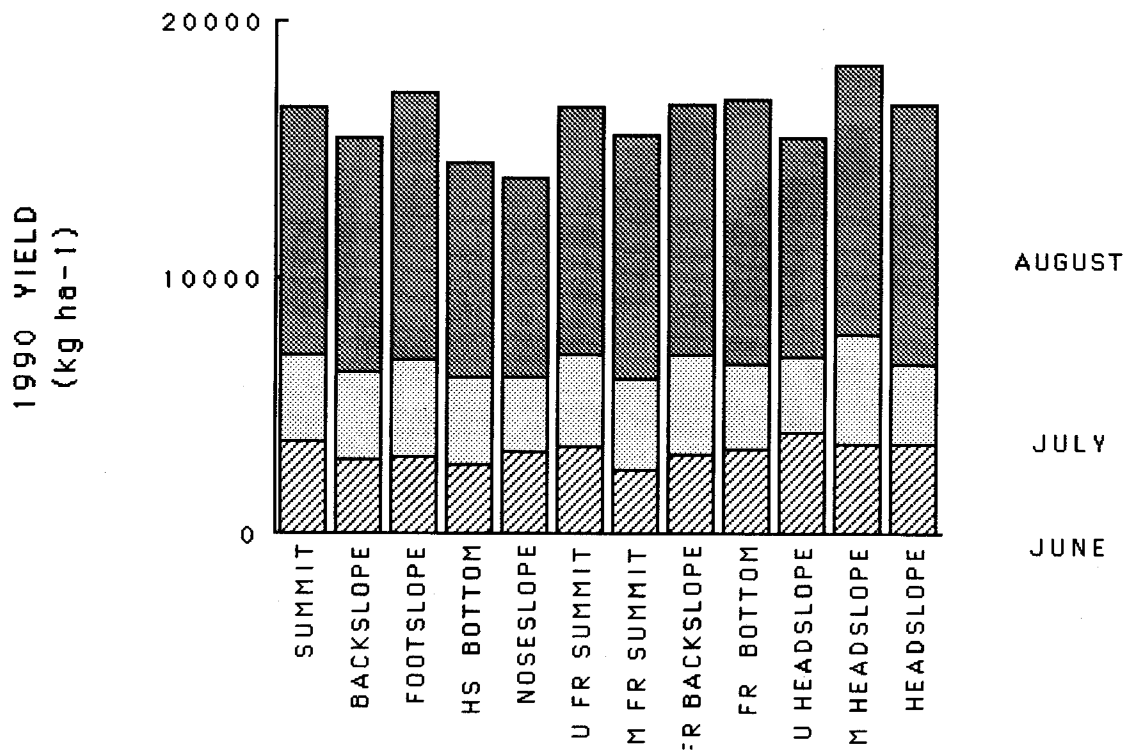

Figure 11. Total 1989 forage yield on Taberville Prairie, Missouri (from Conway-Nelson, 1991).

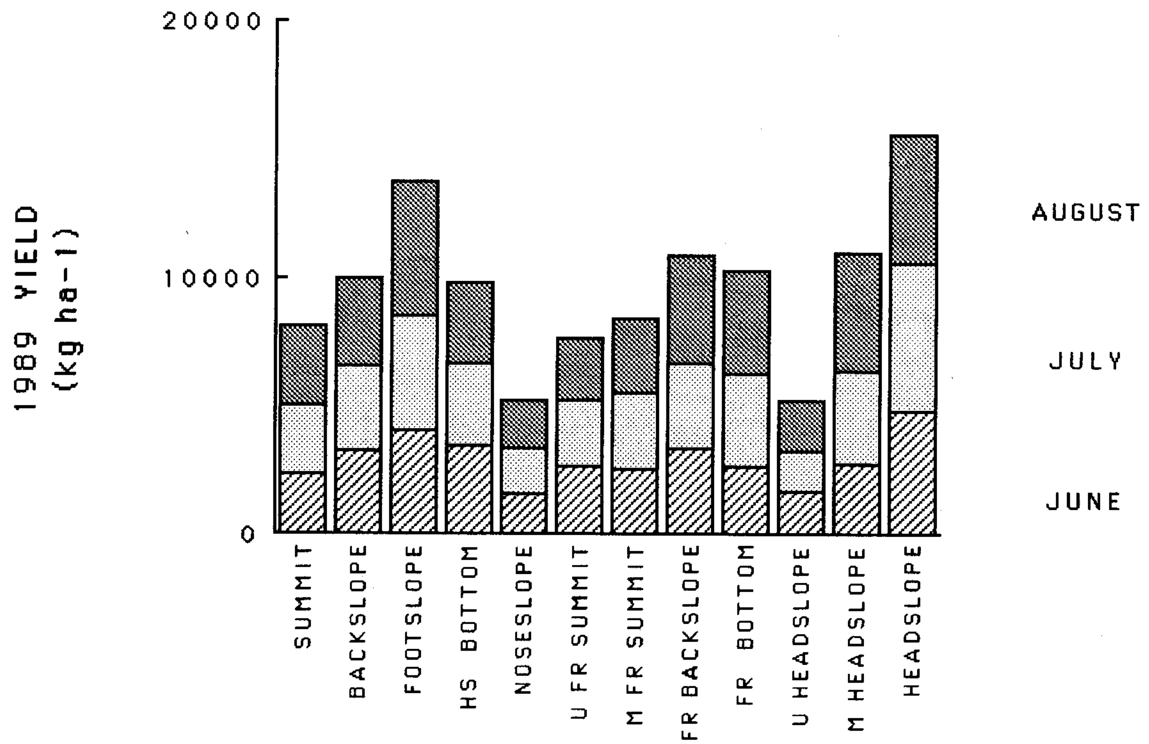

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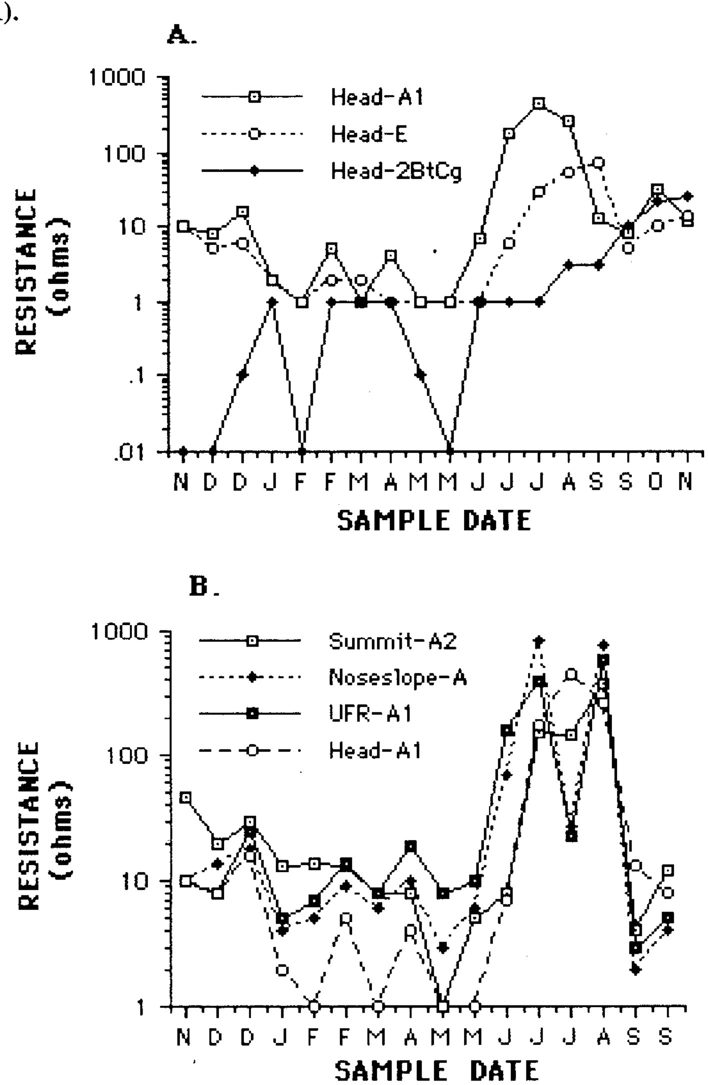
Figure 12. Water yields as indcated by resistance cell readings in a headslope profile (A) and hillslope transect (B) on Taberville Prairie, Missouri. Higher resistance readings indicate lower soil water conditions. Sampling was at three-week intervals beginning in November (from Conway-Nelson, 1991).



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Mapping and Classification of Minesoils: Past, Present, and Future

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Abstract. There was a time when reclamation of mined areas was not considered important in mining operations. After an area was mined, the landscape left behind was often simply a consequence of the coal extraction process. With passage of reclamation laws, notably the Surface Mining Control and Reclamation Act (SMCRA), reclamation became a routine part of mine operations. The soils left behind, once considered simply as spoil, became subject to intense management considerations. This is as it should be because the reclaimed soils will be around long after the coal is gone. This paper discusses the evolving concepts of reclaimed mine soil and presents a proposal for more intensive mapping and classification of this important resource.

INTRODUCTION

One of the purposes of surveying soils is to identify, on maps, soils that have similar use and management. Information in a soil survey report includes soil properties, soil classification, and use and management statements. Since the early 1950's these precepts guided soil survey on undisturbed lands, but in recent years environmental and planning concerns have greatly expanded the researches needed in soil survey and the uses of soil survey. One of the expanded uses of soil surveys in the past 15 years has been their application to surface mining and reclamation problems. The objective of this paper is to present and discuss the development of the mapping and classification of minesoils in response to these mining and reclamation problems.

MAPPING AND CLASSIFICATION OF MINESOILS

The Past

Research on the revegetation of surface mined land in the midwest dates back to the late 1920's (Croxton, 1928), but it was not until the 1940's that attempts were made to classify mine spoils (Lyle, 1980). An early attempt to devise a limited classification system was presented by Tyner and Smith (1945) in West Virginia. Their system of classification was in response to the 1945 West Virginia law which involved the establishment of vegetation on spoil. By classifying the spoil according to the prevailing surface hydrogen-ion concentration they determined which spoils were favorable for plant growth. As part of the classification they also related surface hydrogen-ion concentration to the geologic sections of the mined areas. It is interesting to note that the term "soil" was not used in their research to describe the plant growth material left from mining (spoil). At that time the spoil material was considered a by-product of the surface mining operation.

Limstrom and Deitschman (1951) developed a basic classification of spoil banks in Illinois. Acidity and texture of the of spoil materials were the two factors considered in the classification. Some of the spoil types described were: calcareous sand; acid silty clay loam; and calcareous silty clay. Their study revealed that the nature of surface mine spoils was a result of the character of the overburden and the method of mining used. The results of their classification system were used to determine the suitability of spoils for forest plantings. In another Illinois study, Grandt and Lang (1958) applied Limstrom's (1948) classification system to determine the suitability of the soil material from surface mined land for legume and grass growth. In both studies (Limstrom and Deitschman, 1951; Grandt and Lang, 1958) the spoil material was referred to as soil-sized particles and soil material. By this time, spoil material was beginning to be viewed as a soil or soil material.

During the late 1950's and 1960's, areas affected by surface mining were delineated on soil maps and identified only as mine dump or strip mine (Fehrenbacher and Odell, 1959; Wascher et al., 1962). Soil surveys completed during the 1970's generally identified the mined land as Orthents, a suborder classification of the USDA Soil Taxonomy system (Soil Survey Staff, 1975). In some instances the graded mine spoil was classified differently than the ungraded spoil, as in the St. Clair County, Illinois soil survey (Wallace, 1978); or the acid spoil was differentiated from the nontoxic spoil, as in the Saline County, Illinois, soil survey (Miles and Weiss, 1978). Texture modifiers were also used in some instances. In both counties, the soil map unit descriptions for Orthents included descriptions of landform shape, soil variability, and interpretations for various land uses. Orthents were also listed in all of the interpretative tables. No representative site or pedon was described in the St. Clair County Survey, but a representative site for Orthents was listed in the Saline County Survey (Miles and Weiss, 1978) with no pedon description.

The Present

Ohio (Rubel et al., 1981) and West Virginia (Wright et al., 1982) were two of the first states to map minesoils, but Ohio was the first to name and classify the soils to the series level. The Morristown, Fairpoint, Bethesda, Enoch, and Barkcamp series were established in 1978 in Belmont County, Ohio. Even with the establishment of mine soil series, pedologists were still slow to define and map different soils (series) within surface mined areas. Pedologists felt that minesoils soils were inherently too variable and that mappable patterns of order were not apparent (Indorante and Jansen, 1984).

The reason for this view was the lack of a conceptual model that provided a basis for expecting order and allowed a trained pedologist to readily map it (Indorante and Jansen, 1984). On undisturbed land a soil genesis model is useful, but in areas disturbed by surface mining the soil genesis model applied in the usual way does little to help perceive spatial order. Mine soils are so young that the active factors of soil formation have had little or no effect. The lack of an appropriate conceptual model can cause the apparent complexity to be overwhelming, thus preventing the perception of order which is necessary to classify and map soils.

Indorante and Jansen (1984) proposed a conceptual soil-landscape model useful for perceiving order on surface mined land. With perception of order, mine soils can be mapped and classified. The concept postulated a relationship between soil character and: (1) mining methods; (2) reclamation or soil construction procedures; (3) preminesoils; and (4) premine geologic column. The procedure for applying the model is presented in Figure 1, and was successfully applied (Table 1, Figure 2) to the minesoils in the Perry County, Illinois Soil Survey (Grantham and Indorante, 1988).

Table 1. Chart for minesoil classification in Perry County, Illinois.

Method of soil construction	Shovel	Shovel, dragline, or dragline & dozer	Mining wheel or dragline & dozer	Scraper or scraper & dozer
Overburden texture after mining	Loamy	Loamy	Loamy	Silty
Rock fragments in control section	>35%	15-35%	<15%	<10%
Presence of carbonates in control section	Yes	Yes	Yes	No
Classification	Loamy-skeletal mixed (calc.), mesic Typic Udorthent	Fine-loamy, mixed (calc.), mesic Typic Udorthent	Fine-loamy, mixed (calc.), mesic Typic Udorthent	Fine-silty, mixed (non-acid) mesic Typic Udorthent
Series	Morristown	Lenzburg	Schuline	Swanwick

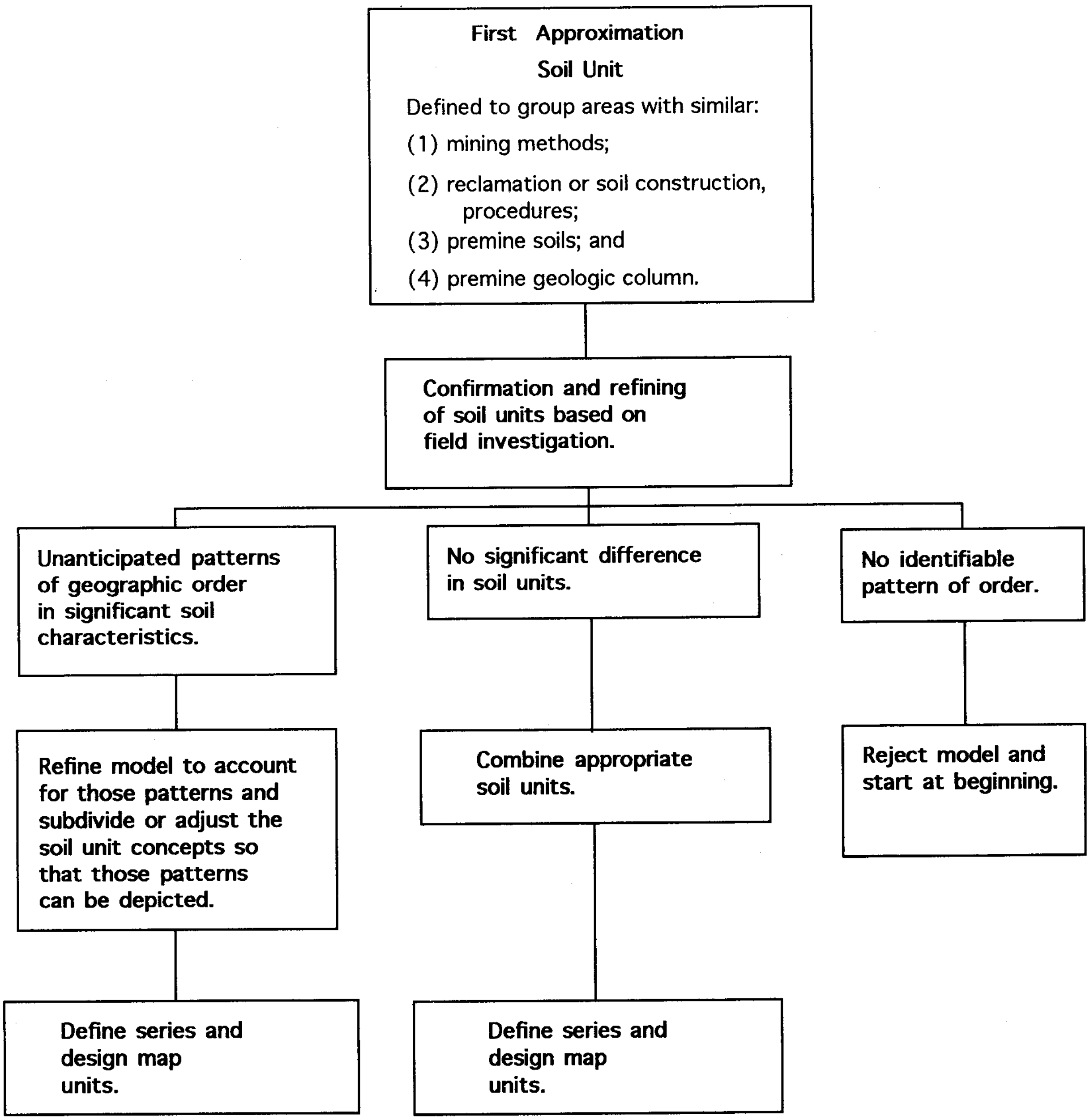
Adapted from Indorante and Jansen, 1984.

The Future

Many more mine soil series have been established and mapped since the original Ohio and West Virginia minesoil series (Soil Survey Staff, 1990). The soil series are Typic Udorthents, with particle size class (which includes rock fragments), reaction class, and soil temperature class being the main differences among the series. Researchers (Sencindiver, 1977; Smith and Sobek, 1978; Thurman and Sencindiver, 1986; Ammons and Sencindiver, 1990), however, have shown that the unique and important properties of minesoils are not always adequately defined by existing taxa within *Soil Taxonomy* (Soil Survey Staff, 1975).

To better define the taxa for minesoils, West Virginia researchers (Sencindiver, 1977; Smith and Sobek, 1978) proposed an amendment to *Soil Taxonomy*. The proposed amendment would create the suborder Spolents to encompass minesoils and other disturbed soils (Thurman and Sencindiver, 1986). Within this suborder are subgroups which are based on the lithology of the rock fragments in the particle size control section (Sencindiver, 1977; Smith and Sobek, 1978). Even though Spolents has not yet been formally adopted by

Figure 1. Flowchart for appying a conceptual soil landscape model to map and classify mine soils (after Indorante and Jansen, 1984).



Soil Taxonomy, the subgroup has been successfully applied to the mapping, classification, and interpretation of minesoils (Sencindiver, 1977; Smith and Sobek, 1978; Ciolkosz et al., 1985; Thurman and Sencindiver, 1986; Ammons and Sencindiver, 1990).

Other researchers have also described the need to develop and use new techniques and terminology to describe and characterize minesoils and drastically disturbed lands. McSweeney et al. (1984) proposed the term *fritted* to describe the artificial structure unique to constructed soils, and suggested that soil series separations should be made on the basis of these types of structural differences. Many properties of the mine soils are temporal in nature (eg. soil compaction) and this poses a special mapping and classification problem. Tugel et al. (1991) have designed a new type of map unit, an *undifferentiated association*, to describe and identify areas with on-going soil modification. The map unit is designed to describe spatial variability in soil properties that are use dependent and therefore a function of time. This scheme may very well fit the special mapping, classification, and interpretive needs of minesoils and drastically disturbed soils.

A Proposal For Improved Mine Soil Classification

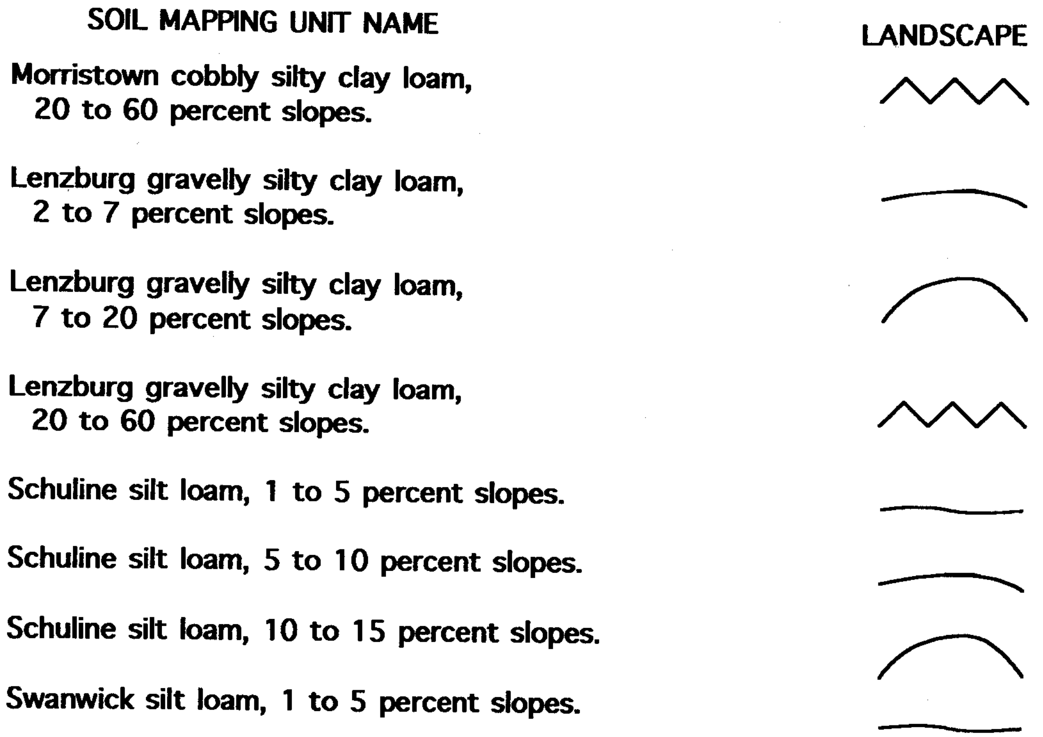
The mapping and classification of soils after surface mine reclamation should be an important part of the reclamation process. To best provide for post reclamation land use and to evaluate and understand reclaimed soils, a classification system needs to be developed that addresses the unique characteristics of mine soils. As in natural soils, many important soil properties can be quickly portrayed if reclaimed soils are well classified and mapped. Soil mapping and classification techniques developed for natural soils may not be appropriate for reclaimed landscapes.

Classification of mine soils should recognize both the attributes inherited from the pre-mine soils and pre-mine geological column as well as those consequential to reclamation methods. Inherited properties of mine soils include soil texture, coarse fragment content, pH, and topsoil color and thickness. Properties resulting from reclamation include density or compaction, slope, drainage, top soil thickness, and coarse fragment content.

The current soil classification scheme for mine soils is inadequate. Mine soil series are primarily focused at characterizing mine soils that were not reclaimed at all or were reclaimed prior to the Surface Mining Control and Reclamation Act (SMCRA) permanent program. This scheme is inadequate given the diversity of mine soils and changes in reclamation. There are thousands of acres of reclaimed mine soils that are not adequately classified.

Reclamation technology has improved as research has demonstrated limitations of old methods and introduced new methods. A new reclamation technique

Figure 2. Soil mapping units and corresponding landscapes for soils on surface-mined land in Perry County, IL (after Indorante and Jansen, 1984).



involving plowing to 1.2 m (48 in) deep has profound effect on soil properties and should be recognized in mapping and classifying of mine soils. Productivity indices assigned to existing series are not applicable to mine soils using improved reclamation techniques. Mine soils which have met productivity standards and mapped under the present scheme are under-assessed causing reduced property tax revenues to counties. This misclassification also reinforces the misconception that a mine soil is not adequately reclaimed under the law.

Problems with existing mine soil classifications include the failure to recognize the single most important factor limiting use and management in many cases. Research at the University of Illinois (Dunker et al., 1991) has identified compaction as the limiting factor in reclaimed mine soils in Illinois. Given the favorable chemical and textural characteristics of the soil materials, compaction resulting from certain reclamation methods is what usually limits crop yields by restricting root growth. The USDA soil classification scheme (Soil Survey Staff, 1975) recognizes root restricting soil layers and assigns a special symbol "d" to the layer. The top of a "d" layer is called a paralithic contact. If a paralithic contact is found within 50 cm of the soil surface, the soil is classified as shallow. There is a new technique involving a continuously recording penetrometer that shows promise in detecting the presence of a root restricting layer (Hooks and Jansen, 1985). This tool could be used to delineate areas of mine soils with compaction problems.

Another characteristic of mine soils that needs to be recognized is the thickness and organic matter content of the replaced surface layer or "A" horizon. In Illinois, for example, there are prairie soils that have a very dark and thick A horizon. Soils that developed under forest vegetation have thin and light colored A horizons. Productivity of these two soil types is different and the mine soils derived from such dissimilar materials should be recognized.

A third important, but currently unrecognized, criteria is drainage. Most mine soils are reclaimed in such a way that they are well or moderately well drained. In some cases mines may be reclaimed to produce wetter soils with somewhat poor or poor drainage. The classification scheme needs to allow for these wet soils.

Table 2 gives the criteria for classification of mine soils to taxonomic family. Soil series criteria are given in Table 3. There will be additional subdivisions of mine soils that recognize slope and unusual features such as acid subsoil or excessive stones in the surface. These special situations will be handled by series phases and map units. Description and classification of mine soils follows conventional pedological techniques given in the USDA soil survey manual (USDA, 1990).

Surface color has two classes. Dark colored soils have a surface horizon that is ≥15 cm thick with crushed color value ≤3 moist and ≥5 dry. These soils also have >1% organic carbon in the surface horizon and a base saturation ≥50% in the upper 100 cm. Surface horizons which do not meet these criteria are classified as light.

Moisture regime in the central part of the interior coal mining region includes Udic and Aquic subclasses. Wet soils are classified as Aquic. These soils show gley colors (chroma ≤2, value ≥4.5, moist) within 50 cm of the soil surface. Care must be taken to assure that the gley colors are due to wetness and not to inherited

Table 2. Sugested minesoil taxonomic family classification criteria for central part of interior coal mining region.

	Class					
Criteria	A[1]	B	C	D	E	F
1. Surface color	light (Ochric)	dark (Mollic)				
2. Moisture regime	Udic	Aquic				
3. Rooting depth	shallow	deep				
4. Reaction	acid	nonacid	calcareous			
5. Texture family	fine	fine silty	fine loamy	loamy-skeletal	clayey	loamy
6. Base saturation, surface	<50%	≥50%				
7. Base saturation, subsurface	<35%	≥35%				

[1]See text for definition of classes.

colors. Accessory field evidence such as landscape position or water table records may be necessary to support the Aquic classification. Soils that do not have gley colors within 150 cm are not wet and are classified as Udic.

Soil depth has two classes. Shallow soils have a root restricting layer within 50 cm of the surface. This can be identified by a bulk density greater than 1.6 g/cc and a lack of roots under deep rooted crops. An additional identification technique is the penetrometer. Penetrometer values greater than 2 MPa when the soil is at or near field capacity is considered root restricting, values of 1-2 MPa are considered root limiting (USDA, 1990).

Reaction class is an evaluation of the pH of a soil. Mine soils that have free carbonates which react to dilute HCl are calcareous. Nonacid soils have a pH of 5.0 or more in 0.01 M Ca Cl2(2:1). Acid soils have a pH of less than 5.0 in 0.01 M CaCl2(2:1).

Texture families are defined in Soil Taxonomy (SCS 1975) and refer to the fine-earth fraction (<2mm) of the upper 100 cm. If there is a root restricting layer, the texture of the material above the layer is included in assessing the family texture class.

Table 4 gives some properties of existing and proposed soil series for mine soils. Because of the lack of good alternatives, the existing soils series have been used in a very broad sense. They would have to be redefined and restricted to a narrower range of soil properties. Their definitions and descriptions would have to include consideration of properties imparted upon the soils by modern reclamation techniques. The tentative classification of the proposed new series, as well as revisions of the existing series are given in Table 5.

As knowledge of mine soils is gained, the need to better manage and evaluate these soils becomes both possible and necessary. A classification system for mine soils will enable the reclaimed soils to assume their rightful place in the landscape.

CONCLUSION

The view of mining and reclamation has changed dramatically over the years. What was once considered a by-product of surface mining is now considered a soil resource to be studied, characterized, mapped, classified, and interpreted. This change in viewpoint reflects society's concern for the environment, and emphasizes the main objective of reclamation which is to construct a land resource of maximum feasible utility and versatility for future generations (Jansen, 1982). Accurate and precise description of soil properties and, spatial and temporal variability are critical to understanding the impact of reclamation practices and the optimum use of the constructed land resource. As reclamation technology and practices continue to change to meet the demands of producing a quality land resource, so must our ability to accurately describe, map, and classify this resource.

Table 3. Suggested minesoil series and phase placement criteria for central part of interior coal minning region.

	Class				
Criteria[1]	A	B	C	D	E
1. Topsoil thickness (in.)	<2	2-6	6-12	>12	
2. Topsoil texture	silt	silty clay loam	silty clay loam	clay loam	loam
3. Rooting media thickness (in.)	0	1-30	30-42	>42	
4. Soil drainage	well	moderately well	somewhat poorly	poorly	
5. Depth to compaction	0-10 (in.)	10-20	20-40	40-60	>60
6. Penetrometer resistance[2] (Avg. 9-48 in.)	<1 MPa	1-2 MPa	>2MPa		
7. Slope (%)	0-5	5-10	10-25	25-50	>50
8. Surface stonyness	<15	15-35	>35		
9. Subsurface stonyness (vol%)	<15	15-35	>35		

[1] Criteria adapted from draft of USDA soil survey manual and are presented for discussion.

[2] Penetrometer resistance is measured when soils are at or near field capacity.

Table 4. Properties of revised existing and proposed new soil series for mine soils in the central portion of the interior coal mining region.[1]

Soil Series	Surface Texture	Soil Color	Drainage	Permeability Surface	Sub-Surface
Lenzburg 871	SiL,SiCL,CL,L	light	well	mod slow	mod slow
Morristown 821	SiL,SiCL,CL,L	light	well	mod slow	mod slow
Schuline 823	SiL, SiCL, CL,L	light	well	mod	m slo-slo
Swanwick 824	Sil,SiCL	light	m-well	mod slow	m slo-v slo
Rapatee 872	SiL,SiCL	dark	well	mod slow	m slo-v slo
Galum*	SiL,SiCL,CL,L	light	well	mod	m slo-slo
Fairview*	SiL,SiCL	dark	well	mod slow	m slo-slo
Pyatts*	SiL,SiCL	light	m-well	mod slow	m slo-v slo
Tablegrove*	SiL,SiCL	dark	m-well	mod slow	m slo-v slo
Captain*	SiL,SiCL	light	well	mod	mod slow
Industry*	SiL,SiCL	dark	well	mod	mod slow
Burningstar*	SiL,SiCL,CL,L	light	well	mod	mod slow
Riverking*	SiCL,SiC,C	dark	s-w poor	m slo-v slo	m slo-v slow
Dupo*	SiCL,SiC,C	dark	s-w poor	m slo-v slo	v slo
Du Quoin*	SiL,SiCL,CL,L	light	s-w poor	mod	m slow

(Continued)

Soil Series	Coarse Fragments(%)[+] Surface	Subsoil	Soil Slope(%)	Rooting Depth	Soil Replaced (in.) Top Soil	Root Media
Lenzburg 871	0-35	10-35	0-70	deep	0	0
Morristown 821	15-50	35-80	0-70	deep	0-12	0
Schuline 823	0-15	0-15	0-15	deep§	6-10	0
Swanwick 824	0-10	0-15	0-10	deep§	6-12	36-42
Rapatee 872	0-20	0-20	1-15	deep§	6-18	36-42
Galum*	0-15	0-15	0-15	deep	6-10	0
Fairview*	0-15	0-15	1-15	deep	6-18	0
Pyatts*	0-15	0-15	0-12	shallow	6-12	36-42
Tablegrove*	0-15	0-15	0-12	shallow	6-18	30-42
Captain*	0-15	0-15	0-12	deep	6-12	36-42
Industry*	0-15	0-15	0-12	deep	6-18	30-42
Burningstar*	0-15	0-15	0-12	deep	6-12	36-42
Riverking*	0-15	0-15	0-5	deep	6-12	30-42
Dupo*	0-15	0-15	0-5	shallow	6-18	30-42
Du Quoin*	0-15	0-15	0-5	deep	6-12	36-42

[1] Adapted from Darmody, R.G., R.E. Dunker and D.L. Spindler. Classification and mapping of reclaimed mine soils. Prime Farmland Reclamation After Surface Mining, Fourth Annual Report 1991. Dept. of Agronomy, University of Illinois, Urbana, IL.

* Proposed series: There may be need for additional series with different texture families etc. Research is needed to establish proposed series properties and to verify existing series properties. Galum is essentially a deep (>40 in.) tilled Schuline. Fairview is essentially a deep (>40 in.) tilled Rapatee. Captain is a deep tilled Swanwick.

§ Compaction: soils with a layer ≥4 in. thick with an upper surface within 40 in. of the soil surface with a penetrometer resistance > 2MPa and an average penetrometer resistance >1.8 MPa in the 10-40 in. depth are considered compacted. Compacted layers also have high bulk density (>1.6g/cc) and should be designated as Cd. The compaction also stops roots and should be considered a paralithic contact. If the paralithic contact is within 50 cm of the soil surface the soil should be classified as shallow. Values for penetrometer resistance and bulk density are provisional and subject to change.

[+] Coarse (2- 25mm) fragments by volume.

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Table 5. Classification of revised existing and proposed new soil series for mine soils in the central portion of the interior coal mining region.[1]

Soil Series	Proposed Classification[¤]
Lenzburg 871	fine-loamy, (calcareous), mixed, mesic, Typic Udorthent
Morristown 821	loamy-skeletal, (calcareous), mixed, mesic, Typic Udorthent
Schuline 823	loamy, (calcareous), shallow, mixed, mesic, Typic Udorthent
Swanwick 824	loamy, nonacid, shallow, mixed, mesic, Typic Udorthent
Rapatee 872	loamy, nonacid, shallow, mixed, mesic, Mollic Udorthent
Galum*	fine-loamy, (calcareous), mixed, mesic, Typic Udorthent
Fairview*	fine-silty, nonacid, mixed, mesic, Mollic Udorthent
Pyatts*	loamy, nonacid, shallow, mixed, mesic, Alfic Udorthent
Tablegrove*	loamy, nonacid, shallow, mixed, mesic, Mollic Udorthent
Captain*	fine-silty, nonacid, mixed, mesic, Alfic Udorthent
Industry*	fine-silty, nonacid, mixed, mesic, Mollic Udorthent
Burningstar*	fine-loamy, nonacid, mixed, mesic, Alfic Udorthent
Riverking*	fine, nonacid, mixed, mesic, Mollic Haplaquent
Dupo*	clayey, nonacid, shallow, mixed, mesic, Mollic Haplaquent
Du Quoin*	fine-loamy, (calcareous), mixed, mesic, Aeric Haplaquent

[1] Adapted from Darmody, R.G., R.E. Dunker and D.L. Spindler. Classification and mapping of reclaimed mine soils. Prime Farmland Reclamation After Surface Mining, Fourth Annual Report 1991. Dept. of Agronomy, University of Illinois, Urbana, IL.

[¤] The existing soil series are currently classified as mixed, mesic, Typic Udorthents. Some of the proposed as well as the existing series may be Udarents. Schuline, Swanwick, and Rapatee need to be redefined as shallow and loamy.

* Proposed.

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Evaluation of Grain Crops on Reconstructed Prime Farmland

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Abstract. An ongoing project to determine the yield potential of several grain crops on reconstructed prime farmland is being conducted in western Kentucky. Crops being evaluated include: grain sorghum, wheat, and soybeans. In some cases, yields for non-mined land are also reported. Significant differences between varieties for each crop were obtained. It would appear that selection of certain varieties for each crop would be to the advantage of coal companies in their use of these crops in proving performance standards for Phase III bond release of prime farmland. However, since the ranking is not consistent from year to year, caution should be exercised in making specific variety recommendations.

INTRODUCTION

Proof for the restoration of the productivity of prime farmland is currently based on crop yields for three years. Coal mine operators have some latitude in selecting which crop they may grow in order to determine productivity. In addition to forage or hay crops, grain crops such as corn, wheat, soybeans, and grain sorghum are commonly planted in mid-western states. In Kentucky, as well as most all of these states, corn must be grown and the target yields equaled or exceeded one of three years under consideration for Phase III bond release. The overall objective of this research was the evaluation of grain sorghum, wheat, and soybean varieties over a five-year period on restored prime farmland. However, to date only the collection of grain sorghum yield data has been completed. Variety evaluation of corn is the subject of other papers (Powell et al., 1988 and Poneleit et al., 1992).

MATERIALS AND METHODS

Reconstruction Procedures

All data reported in this paper were collected on the River Queen and Alston Surface Mines operated by Peabody Coal Co. in Muhlenberg Co. and Ohio Co., respectively. The prime farmland soils were reconstructed using scraper pans. The dominant soil types that occurred on these mines were the Sadler silt loam (fine-silty, mixed, mesic Glossic Fragidulfs) and the Belknap silt loam (coarse-silty, mixed, acid, mesic Aeric Fluvaquents).

The two soil types were mixed together in a temporary stockpile in the process of surface mining. At the River Queen Site approximately 75% of this mixture was Sadler, with the remainder being Belknap. At the Alston mine, the two soils were approximately in the same proportion. At both sites, the mixture of subsoil was placed over graded spoils to a depth of 36 inches, leveled with a dozer, and approximately 8 inches of topsoil was placed on this graded subsoil.

Soil Fertility

The soil was limed to 6.4 by incorporating 2-4 tons/acre into the leveled topsoil with a heavy-duty disk. Lime rates were based on Kentucky Cooperative Extension Service Recommendations in AGR-1 (Anonymous, 1985*). Lime was needed only the first year of the experiment.

Rates for P and K for each grain crop were based on the same publication, AGR-1. These recommendations were made from randomly collected soil samples taken each year, and generally recommendations decreased as the soil test level slowly increased from very low and

* Although a few changes have occurred over the years with respect to recommendations of lime, nitrogen, phosphorus, and potash, all recommendations were taken from this same publication for each crop, i.e. grain sorghum, wheat, and soybeans.

medium for P and K, respectively. The rates of P_2O_5 initially applied were 120, 120, and 150 lbs/acre for soybeans, wheat, and grain sorghum, respectively. For K_2O, rates were 50, 40, and 100 lbs/acre for soybeans, wheat, and grain sorghum.

RESULTS AND DISCUSSION

Grain Sorghum

Grain sorghum has several traits that may reduce the risks for crop failure on reconstructed prime farmlands. It withstands drought stress better than corn or soybeans by becoming semi-dormant. This has been attributed to its fibrous root system which tends to increase its efficiency in extracting water. The evapotranspiration tends to be lower than corn, and pollination does not seem to be as severely affected by high temperatures. When moisture and nutrients are adequate, grain sorghum produces tillers or extra seed heads that will contribute to higher grain yield, but during drought periods only the primary tiller will produce a seed head. Grain sorghum also withstands excessive moisture conditions better than either corn or soybeans.

The grain sorghum varieties were planted in 30-inch rows at 7 lbs of seed per acre. Each plot or variety consisted of 2 rows, 38 feet in length. Five replications were used in a randomized complete block experimental design. In general, plots were planted the second week of May and harvested when the grain was dry enough to be thrashed with a MF plot combine. Yields were adjusted to 14% moisture.

Grain sorghum yield data are given in Table 1. The varieties planted each year varied somewhat during the 5-year period due to availability from seed suppliers and availability of plot space. The target yield for grain sorghum has not been established by the USDA-SCS, however subtracting the long-term (20-year) state aver-

Table 1. Grain sorghum hybrid test results on reconstructed soil, Peabody Coal Company—River Queen Mine.

Brand-Hybrid*	Maturity Group	Yield** 1985	1986	1987	1988	1989
		bu/a				
Pioneer 8333	3	53	60	65	39	102
Asgrow GS712	4	—	61	46	76	94
Funks G1711	4	63	55	51	58	94
TE Y75	2	—	43	43	81	94
Pioneer 8515	3	53	60	66	28	92
DeKalb DK424	2	57	—	51	40	87
NK S9740Y	2	—	—	—	54	86
TE Y101G	3	77	48	57	45	86
Asgrow Mustang	3	—	57	71	42	86
TE Dinero	3	68	44	40	41	85
NK 2778	3	81	62	70	—	83
NK 2660	3	64	53	31	53	80
Asgrow Topaz	3	63	37	50	45	78
NK 734G	3	—	—	—	33	69
Funks G522DR	3	69	42	39	51	67
Funks RA787	2	—	—	—	57	65
DeKalb M565	2	—	—	38	50	58
NK 2779	3	—	—	48	39	55
TE Y35	1	—	—	—	—	31
Garst 5521	3	—	—	—	51	—
Garst 5511	3	—	—	—	46	—
Pioneer 8226	3	—	—	49	38	—
SS SS1313	4	—	—	37	—	—
SS FFR321	3	—	—	36	—	—
TE Y45G	1	62	64	—	—	—
SS SS174	3	53	58	—	—	—
Funks G1602	3	71	50	—	—	—
TE Dinero-E	3	—	42	—	—	—
NK 2244	2	60	—	—	—	—
TE Y77	2	52	—	—	—	—
L.S.D. (.10)		14.5	14.6	14.4	12.0	17.0

* NK, TE, and SS corresponds to Northrup-King, Taylor-Evans, and Southern States, respectively.

** Yields ranked according to 1989 values. Entries with no values were not planted the respective years.

age yield for grain sorghum from corn, a yield difference of 22 bu/a was determined. The pro-rated target yield for the reconstructed prime farmland at River Queen was calculated to be 83 bu/a. An adjusted statistical value may be determined by subtracting the L.S.D.(.10) value from this target yield, which equals 69, 69, 69, 71, and 66 bu/a for 1985 through 1989, respectively.

In 1985, only 4 of 15 varieties equaled or exceeded the target yield, whereas in 1986, none of the varieties produced enough grain to exceed the target value. In 1987, 2 of the 18 varieties exceeded the target. Prior to 1987 yields were reduced due to compacted subsoil, poor weed control, and perhaps low soil fertility. In 1987, the combine was not available for a timely harvest and considerable losses occurred due to birds. Some varieties experienced as much as 25% loss.

In 1988, much of Kentucky was affected by drought. At this experimental site, the effect of drought diminished after July 10 due to scattered thundershowers. Only 2 of the 20 varieties exceeded the adjusted target yield in 1988.

In 1989, all but 4 varieties exceeded the adjusted target yield and 11 of these had a yield greater than the actual target of 83 bu/a.

Five years of data may not be enough to support conclusive recommendations on which varieties are best suited for reconstructed prime farmland soils, however, it is apparent that some varieties consistently yielded higher than others. There did not appear to be a strong relationship between maturity group and yield.

Wheat

Wheat has some characteristics that may be considered advantageous as a grain crop for Phase III bond release. It avoids summer drought by reaching maturity in late June. Winter wheat also provides reduction in erosion by protecting the soil during its growing period. The straw following harvest may be used as a mulch on steeper non-prime farmland soils.

Soft red winter (SRW) wheat has been used extensively in reclamation as a temporary cover crop, nurse crop, and to a limited extent as a cash crop on mine spoils. Soil depth, ripping, and cultivar selection have been shown to be important to wheat production (Barnhisel et al. 1988). In that study, wheat yields increased with topsoil depth between 10 and 20 inches but not much increase in yield resulted between 20 and 30 inches of soil. Ripping significantly increased yields 2 out of 3 years. Wheat yields ranged from excellent (56 bu/a) to poor (18 bu/a) depending on the year and cultivar selected.

The objective of this five-year study is to evaluate wheat varietal performance on reconstructed prime farmland soils and determine whether varietal rankings can be predicted from conventional variety trials grown on non-mined soils. Data given here are for the first full scale trial, although a few varieties were planted in 1989.

Fifteen SRW wheat varieties were seeded in mid-October 1990 in 7-inch row spacings at a seeding rate of 1.5 bu/a. Each variety was sown in 250 foot strips that were 28 feet wide. Each strip was divided into four blocks or replications. Plots were harvested with a MF plot combine by cutting two 2-meter wide strips from each of the four plot areas, 100 feet in length. All yields were adjusted to 12% moisture.

An intensive management system was employed which consisted of split applications of nitrogen. One was applied at planting and three in the spring with a total of 120 N lbs/a. Three applications of foliar

Table 2. Yields (bu/a) and rankings (in parentheses) of soft red winter wheat varieties grown in mine and non-mine soils in 1991.

	Mine	- - - Non-Mine - - -		
Variety	River Queen	Ohio Valley	W. Coal Field	S. Tier
Saluda	42 (1)	31 (6)	8 (13)	33 (8)
Coker 9803	35 (2)	34 (4)	2 (9)	49 (1)
Pioneer Brand 2555	33 (3)	27 (8)	8 (2)	38 (6)
Verne	31 (4)	37 (1)	1 (1)	47 (2)
Coker 916	30 (5)	35 (2)	3 (8)	34 (7)
Coker 833	30 (6)	34 (3)	6 (4)	41 (5)
Becker	27 (7)	22 (10)	11 (10)	25 (12)
Pioneer Brand 2548	27 (8)	23 (9)	7 (3)	43 (4)
Howell	25 (9)	28 (7)	6 (5)	30 (9)
Clark	24 (10)	31 (5)	6 (6)	46 (3)
Excel	22 (11)	12 (14)	9 (12)	25 (13)
Dynasty	21 (12)	21 (12)	14 (7)	26 (11)
Caldwell	20 (13)	20 (13)	6 (14)	20 (14)
Cardinal	18 (14)	21 (11)	11 (11)	30 (10)

fungicides were also applied, two with the last two nitrogen applications and one additional, as diseases were excessive in 1991.

Yield data for 1991 are presented in Table 2. This table includes data for the fourteen varieties planted at River Queen and for these same varieties planted at three locations in the conventional variety trials. Across Kentucky, and in the state variety trials, wheat yields in 1990 easily surpassed those of 1991 (Van Sanford et al., 1991). This same trend was observed at River Queen for the few varieties planted for the 1990 harvest. Yields for varieties planted at River Queen, Saluda, Pioneer 2555, Becker, Howell, Clark, Dynasty, Caldwell, and Cardinal were 40, 44, 35, 36, 34, 39, 45, and 38, respectively. In 1991, spike disease, such as scab and glume blotch, severely limited yields and were generally not amenable to chemical control.

In spite of the similarity between the mine study and conventional variety trials, there are differences which require comment. It is notable that the top variety in the 1990 River Queen test, Caldwell, and the top variety in 1991, Saluda, are both viewed as varieties that have passed their peak performance. The popularity of each has dwindled, and neither has fared very well in variety trials in the past two years. For example, Caldwell received the lowest ranking of any variety evaluated in 1990-91 in the state trials, and Saluda was ranked in the lowest one-third of that group (Van Sanford et al., 1991).

The 1991 mine data are compared with data from three variety trial locations in Table 2. As a measure of correspondence between mine and non-mine sites, one can look at rank correlation coefficients for varieties. The rank correlation coefficients for the River Queen and the Western Coal Field, Ohio Valley, and Southern Tier sites were $r = 0.24$, 0.69, and 0.60, respectively. One can attribute a lack of correspondence to simple genotype x environment interaction which is common among all locations in the state variety trial. It is not possible, at this point, to identify the factors unique to the mine soil environment which would inflate the genotype x environment interaction. The other issue that must be considered is the management regime for each of the trials. In the state variety trial, diseases are not controlled with fungicides. This clearly can have a dramatic impact on varietal performance.

Soybeans

Since the soybean is a legume, it will supply nitrogen for its growth provided the needed bacteria are supplied through seed inoculation. Soybeans may also be used in a double-crop management system that could provide data for two grain crops in a single year. However, reconstructed prime farmland that has marginal soil available water holding capacity due to a heavier texture or compaction, may not produce high enough yields for Phase III bond release unless an adequate rainfall distribution occurs.

The soybean varieties were planted in four, 30-inch rows at a rate of 1 bu/acre. The length of each plot was 38 feet and organized in a randomized complete block experimental design with four replications. In general, plots were planted the third week in May and harvested with a MF plot combine. Only three of the four rows were harvested for yield determination. All grain moistures were adjusted to 13% moisture.

Data for soybean yields which have been collected in 1990 and 1991 are given in Table 3. Prior to 1990, yields were collected from several varieties at the River Queen site, but this research had to be discontinued temporarily after one year (1985). Only two of the 14 varieties planted in 1985 have been included in the current project, these were Essex and FFR 516. In 1985, yields for these varieties were 33.7 and 31.9 bu/a, respectively and ranked 2 and 4 of those tested. These earlier data have been published (Barnhisel et al., 1986).

Yields were low at both sites. Both years weeds, especially fall panicum, foxtail, and yellow nutsedge, were not controlled. Weeds were so heavy at River Queen in 1990, plots were not harvested. However, since there did not appear to be any significant difference in weed populations among varieties, values may be considered as relative.

The target yield for Phase III bond release for soybeans (34 bu/a) was not exceeded at either location. Only one variety in 1990 (Pioneer 9531) approached the adjusted target value of 28.3 bu/a. Since these data are preliminary, few conclusions may be drawn with respect to variety selection. Group IV and V maturity ranking has been observed in the earlier study (Barnhisel et al., 1985) to be superior to group III. This is largely expected since our site falls on the general line separating maturity groups.

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Table 3. Soybean yields at two locations on restored prime farmland.

Variety[1]	River Queen 1991	Alston 1990	Alston 1991
	bu/a		
Asgrow 4595	24.8 (1)*	16.0 (12)	11.0 (20)
Jacques J499	24.4 (2)	23.2 (5)	16.1 (12)
TN 5-85 (R)	24.0 (3)	14.3 (17)	16.0 (13)
So. States 516 (R)	24.0 (4)	16.0 (12)	18.6 (5)
Essex	23.2 (5)	17.2 (10)	17.7 (9)
Stafford	24.0 (6)	24.5 (4)	17.6 (10)
Asgrow 5403 (R)	22.5 (7)	23.0 (7)	19.8 (3)
Pharaoh (R)	21.8 (8)	—	18.6 (5)
FFR 561	21.5 (9)	20.2 (9)	21.5 (1)
DeKalb cx458	21.0 (10)	15.4 (14)	13.3 (16)
Pioneer 9531 (R)	20.8 (11)	23.1 (6)	17.1 (11)
So. States 487	20.8 (12)	17.1 (11)	15.5 (14)
Pioneer 9501	20.7 (13)	27.0 (1)	7.9 (8)
Coker 425	20.6 (14)	21.4 (8)	18.9 (4)
TN 4-86 (R)	18.2 (15)	15.2 (15)	15.3 (15)
FFR 565 (R)	16.8 (16)	25.4 (3)	18.3 (7)
Pioneer 9461	15.3 (17)	12.5 (19)	11.8 (19)
Pennyrile	15.2 (18)	13.2 (18)	12.2 (18)
NK 42-40	14.3 (19)	14.5 (16)	9.6 (21)
Spencer	13.1 (20)	9.8 (20)	13.2 (17)
Hutcheson	11.8 (21)	25.5 (2)	20.9 (2)
L.S.D. (10)	4.3	5.7	3.8

*Rank of yield in parentheses

[1] Varieties with R indicates resistance to cyst nematode

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Ecological Succession - - Its Effects on Soil Properties and Implications for Surface Mine Reclamation

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Abstract. Natural succession, which has been studied for nearly a century, has provided important insight into rates and pathways of soil development and clues about ecosystem dynamics necessary to reconstruct damaged ecosystems. Soil chemical and physical properties are improved under primary and secondary succession. Research has shown that soil properties degrade under agricultural practices, and degradation is accelerated under continuous row cropping. Public Law 95-87 requires that reclaimed prime farmland meet or exceed productivity of unmined similar soils. The economic pressure to release the bond mandated by law has resulted in a focus upon achieving crop yield at the expense of reassembling the disturbed ecosystem. This manuscript examines some of the progress made and lessons learned since enactment of Public Law 95-87 and suggests examples of how a change in perspectives would benefit the reclamation process and those engaged in its implementation.

INTRODUCTION

Fifteen years after enactment of Public Law 95-87 (The Federal Surface Mining Control and Reclamation Act of 1977 (SMCRA)), we have gathered at this symposium to discuss progress, problems, and perspectives resulting from reclamation and research in response to the federal mandate. Among the speakers are research scientists with specialties including crops, soils, engineering, and statistics; administrators from state and federal agencies; and representatives of the coal mining and electrical power industries. In attendance are managers, regulators, miners, reclamation specialists, and environmentalists. Other interests and perspectives undoubtedly are represented. Hopefully, among the consequences of the symposium will be: increased awareness of progress made and of remaining challenges; a renewed willingness to work together to build upon what we have learned; and willingness to integrate that which we know, but have not used.

The many individual reclamation perspectives represented here probably have undergone modification with time. A benefit of SMCRA has been the forced focus upon productive reclamation. Many resources have been invested in attempting to find ways to meet bond release on prime farmland. Much of the effort has been in measuring crop response to treatment impacts, with particular emphasis on ameliorating compaction, evaluating crop varieties, and measuring yield response to fertilizer applications. Among the manuscripts at this symposium are 16 which directly address crop yield responses. Six papers address modification of compaction by tillage. Unless titles are deceiving, only this paper addresses soil ecology or alternative uses of reclaimed land. The objectives of this presentation are: 1) to review effects of natural succession on soil properties, 2) to discuss a few aspects from natural succession which are potentially important to reclamation, and 3) to review SMCRA from the perspectives of time and succession.

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NATURAL SUCCESSION

Definition of succession

Plant succession has been studied for nearly a century. North American ecology has its roots in the investigations of ecological succession (Colinveaux, 1986). Consequently, succession has received much attention, various perspectives exist among ecologists (Horn, 1974), and much of the attention has focused upon dynamics of plant communities (Keever, 1983). Time and space limit our depth of treatment. The references we have cited will provide quick access to the important literature.

Primary succession colonizes freshly exposed, unweathered sites and results in the first occupation of the habitat by the climax community. Examples are successions on sand dunes, volcanic mud flows, glacial till, and marshes (Colinvaux, 1986). Abandoned, unreclaimed mine spoils fall into this category. Secondary succession replaces a climax community following a catastrophic disturbance (Colinvaux, 1986). Old field succession following abandonment is the example most commonly investigated and reported (Keever, 1983). Reclaimed surface mine sites would qualify as secondary succession if the topsoil were replaced and nature were allowed to take its course.

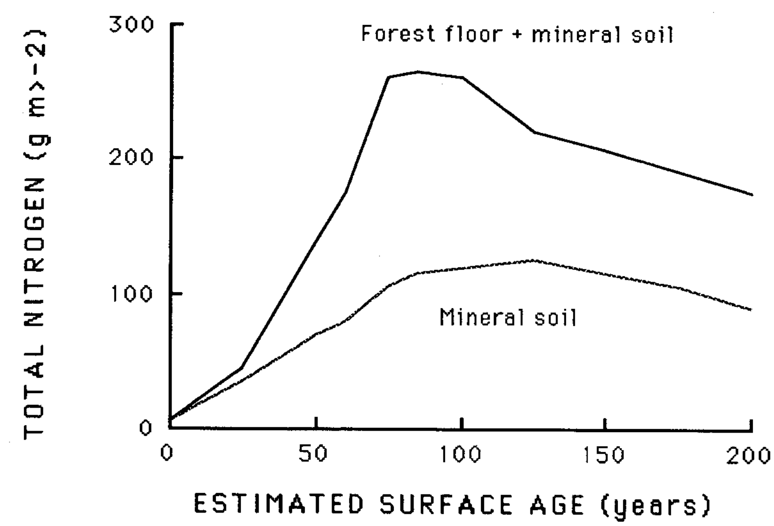
Succession is an organizing process, with some predictable consequences. Early site and habitat improvement by the first colonizers modify conditions and pave the way for later successional species (Colinvaux, 1986). Ultimately, according to Clements (the founder of the "climax theory"), a climax community is established and is noted for the complexity and biomass accumulation (Clements, 1936). Climax species have the unique ability to reestablish themselves on the sites they occupy. Recent ecological concepts recognize the role of soil and nutrients in affecting the rates and directions of successional patterns. Nutrient additions can prolong site occupancy by some species and favor the presence of some over others (Bush and Van Auken, 1986). Cause and effect relationships among individual plant species and soil development often are difficult to demonstrate (Bush and Van Auken, 1986), although investigators commonly credit some plant species as being "soil builders" or "site degraders" (Miles, 1985). Stone's (1975) eloquent treatise of this topic should be required reading for all who are interested in soil development.

Effects of succession on soil development

A few investigations of effects of succession on soil development have become classics among ecologists and pedologists (Birkeland, 1984). Crocker and Major (1955) studied soil development related to plant succession on Alaskan glacial moraines. Knowledge of glacial retreat rates allowed them to estimate surface ages, thus determining nitrogen accumulation as a function of time. Figure 1 reveals that N levels in the forest floor (the organic debris overlying mineral soil) reached a maximum in the first 50-60 years, then began to decline. Mineral soil N continued to increase for several decades. The early N accumulation was attributed to legumes such as *Dryas drummondii* and *Sheperdia canadensis* in the understory and *Alnus crispa*—a nonleguminous N-fixing species in the overstory. The N-fixers ultimately were replaced by successors, and the N level reached a dynamic equilibrium between 150 and 200 years.

Leisman (1957) investigated successional dynamic of an iron mine spoil bank in Minnesota. His results (Figure 2) show a rapid surface accumulation of N, with a delayed accumulation at depth. Leisman also noted the presence of legumes in the early stages of succession, and reported that N levels eventually reached a steady-state level.

Figure 1. Accumulation of N in the mineral soil and forest floor during primary succession of glacial moraines in Alaska (adapted from Crocker and Major, 1955).



Mud flows near Mt. Shasta, California, provided a site for Dickson and Crocker (1953) to study primary succession. Organic matter (OM) accumulated rapidly in the soil surface, reaching a steady-state in about 560 years in a pattern similar to Leisman's (Figure 3).

The cited examples of primary succession indicate that steady-state soil OM levels are reached in periods of centuries. However, OM accumulation in secondary succession proceeds more rapidly. The best known early report of secondary succession is Billings (1938) observation of abandoned fields in North Carolina (Figure 4), where organic matter in the soil surface accumulated rapidly, and reached steady state, at a level three times the initial amount, in about 80 years. Old field succession in this region is characterized by a forest climax. Time to establishment of climax is a

Figure 2. Accumulation of total nitrogen with depth and age in Minnesota iron mine spoil banks (adapted from Leisman, 1957).

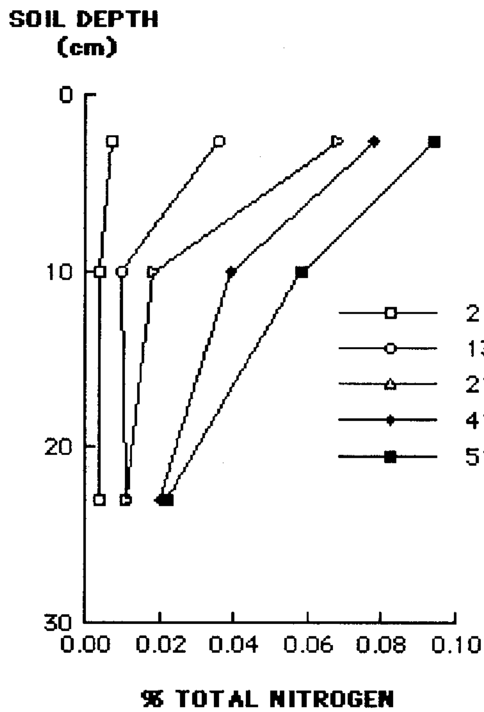


Figure 3. Accumulation or organic carbon as a function of surface age and soil depth near Mt. Shasta, California (adapted from Dickson and Crocker, 1953).

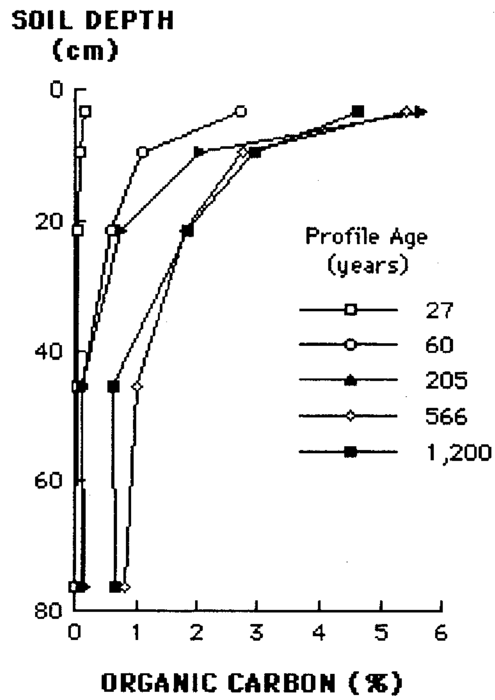
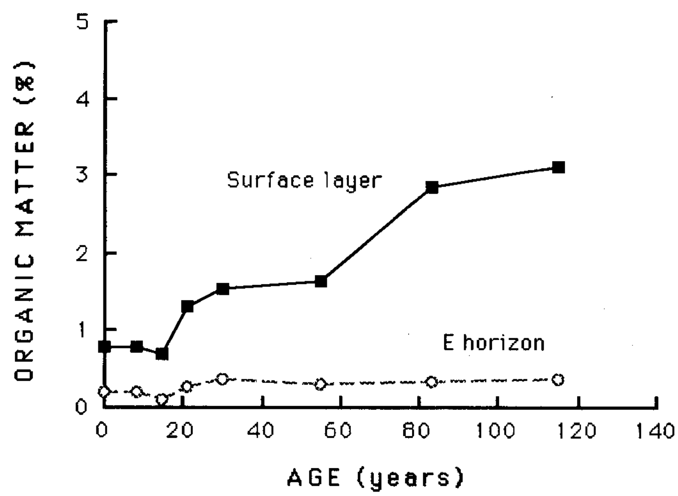


Figure 4. Accumulation of organic matter in the surface soil and E horizon of a forest soil during old field succession in North Carolina (adapted from Billings, 1938).



function, among other factors, of proximity and abundance of seed source (Keever, 1983). The final soil conditions, including O.M. levels and forms and stability of N reserves are a function of climate and parent materials as well as vegetation.

Hammer and Koenig (1988) compared total carbon levels in cultivated soils and adjacent warm season grass stands planted as wildlife habitat in west-central Missouri (Figure 5). Within five years, 0.6 % total C had been added to the surface 5 cm of soil, and total C had increased at all depth increments in the upper 30 cm. Similar OM increases were found in seven and 10-year-old grass stands. Additionally, large earthworm populations were established in the rooting mats of the grasses, and agricultural plow pans, still present in soils between grass clumps, were absent in the root columns beneath individual grass clumps. A thesis project in progress is comparing aggregate stability and water-holding capacities of these soils. Preliminary indications are that soils under the grasses have increased structural aggregation and aggregate stability, decreased bulk density, and higher water-holding capacities. Other investigators have reported rapid OM accumulations under grasses (Dormaar et al., 1990; Stevenson, 1982; Jenkinson, 1971; White et al., 1976). The positive effects of soil OM on structure, porosity, aeration, water-holding capacity, aggregate stability, and cation exchange capacity are well documented (Stevenson, 1982; Birkeland, 1984; Clement and Williams, 1958).

We have briefly established the positive attributes of succession on soil OM, and have concluded by inference that other positive attributes occur as OM levels rise. Bradshaw (1987) said the accumulation of organic matter into the surface soil is probably the most important aspect of succession because it ameliorates the soil physical condition, is the energy source for soil fauna, and is a nutrient- and water-holding source for soil flora.In another setting, Bradshaw (1983) proposed that the greatest hope in ecosystem restoration is "creative ecology which learns from nature's examples."

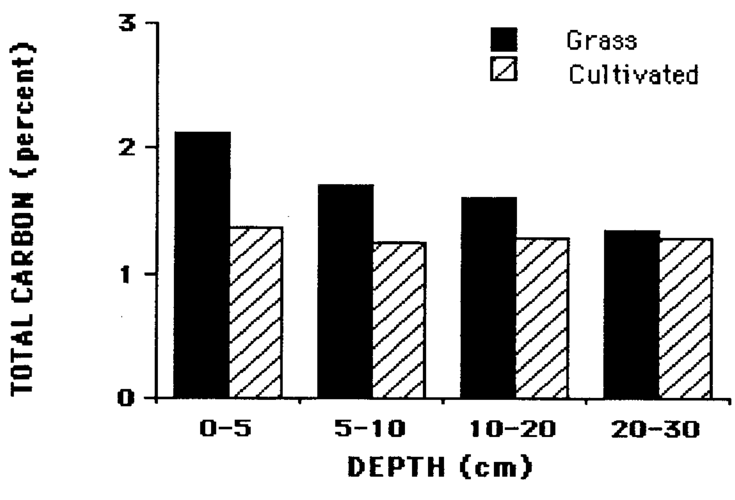
EFFECTS OF CULTIVATION ON SOILS

Research has established that many soil properties are negatively impacted by cultivation. A detailed review is beyond the scope of this paper, but a few key points will be illustrated. For example, McCoy (1987), reviewing past progress and future challenges in soil conservation, lamented the rapidly growing problem of increased compaction in agricultural soils. He cited the demonstrated effects of aggregate destruction on reduced aeration, reduced infiltration, and increased resistance to root penetration. One who reads McCoy's comments cannot help but feel that we who deal with soil compaction in reclamation will soon be joined by agronomists studying related problems created by tillage of agricultural soils.

One of the first reported impacts of cultivation, and one which profoundly affects a host of other soil properties, is loss of O.M. (Jenny, 1941). Jenny observed (Figure 6) a rapid initial loss of soil O.M. with cultivation, with a new, lower, steady-state level being reached in 50 to 60 years. Stevenson (1982) reviewed the subsequent work verifying Jenny's observation.

The loss of soil O.M. with cultivation is accelerated by continuous row-cropping. Larson et al. (1972) found that additions of six t ha^{-1} $year^{-1}$ of plant residue were required to maintain O.M. levels in a Typic Hapludoll in Iowa. When legumes and fibrous-rooted small grains are included in crop rotations, O.M. losses are minimized. Hammer and Brown (1989) reported that 100 years of cultivation on Sanborn Field had not

Figure 5. Total carbon content of cultivated soil and adjacent five-year-old established warm season grass plot. (adapted from Hammer and Koenig, 1988).



destroyed surface or subsoil structure or greatly reduced O.M. levels on plots which had received annual additions of manure in a corn, oats, wheat, red clover rotation. Plots receiving no O.M. and continuously cropped to corn or soybeans were severely eroded, contained only trace amounts of O.M., and were structureless in the plow layer. Barnhisel et al. (1988) reported measurable improvement of soil structure in reclaimed minesoils planted to forage crops. Minesoils in continuous row cropping exhibited very poor surface soil structure and developed platy structure at the base of the plow layer. Unfortunately, the time frame (10 years) allowed by SMCRA for operators on prime farmlands to demonstrate crop productivity results in continuous cropping, with expensive mechanical means often being used to modify compacted soils.

LESSONS FROM SUCCESSION

The role of microorganisms in the nitrogen cycle

Stevenson (1982) observed that microorganisms are necessary in all phases of the soil N cycle, including biological fixation, mineralization, assimilation by soil flora and plants, immobilization, and denitrification. Further, he stated that "... the ability of a few bacteria and blue-green algae to fix molecular N_2 can be regarded as being second in important only to photosynthesis for the maintenance of life on this planet. Soil fauna are necessary precursors, through breakdown of macro debris, for the soil microorganisms (Kevan, 1968). A diverse, robust population of soil organisms and annual returns of O.M. to the soil appear necessary to maintain soil O.M.

Much remains to be learned about the abilities of ecosystems to produce O.M. In addition to N, P and S are essential for O.M. production. Both the quantity and quality of stable humus appear to be affected by these nutrients (Stevenson, 1982).

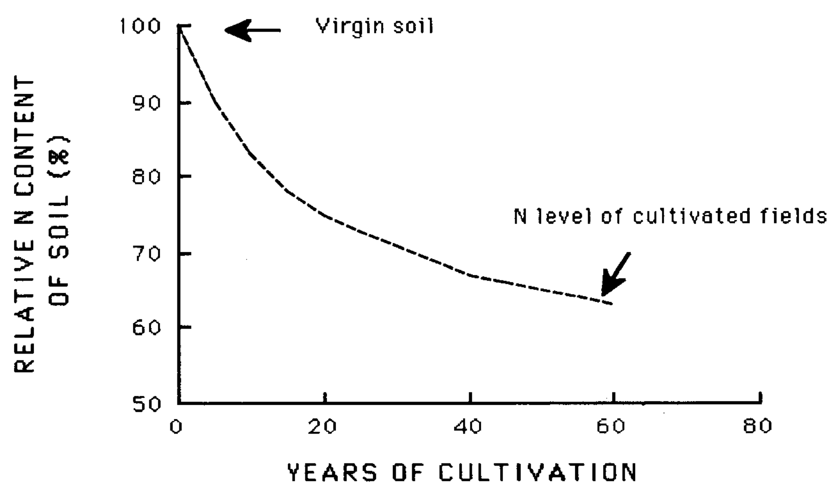
Until recently, microbiologists were limited in their abilities to study soil microorganisms. Schmidt's (1987) review is succinct. He reminded that the majority of soil-born bacteria remain "... unknown to nature, unknown as to function, and inaccessible to isolation." He lamented that the role of soil biota other than fungi an bacteria in generalized interaction including organic matter reduction, biomass accumulation, and grazing, remains largely unknown. However, the International Biological Program (IBP) demonstrated that most of the flow of energy and nutrients in ecosystems is regulated by below-ground events through the activities of soil microorganisms. The soil, to a great extent, has been regarded by ecologists and agronomists as a "black box," into which materials flow and from which different or modified products emerge. Until the internal processes of the "black box" are more clearly understood, our abilities to predict the effects of our activities will remain low.

Recent progress

Jeffries et al. (1981) demonstrated dramatically increased forage production on reclaimed minesoils when legumes were incorporated into the forage mix. The benefits of legumes were observed even when N fertilizers were added to the minespoils. Legumes have been repeatedly observed to be site colonizers in early primary and secondary succession. Much remains to be learned about their role with soil microorganisms in the fixation of atmospheric N and its subsequent conversion to stable forms of humus (Stevenson, 1982).

Some recent progress offers hope that the role of soil microorganisms will receive more attention. Most progress has been in the arena of ecosystem restoration.

Figure 6. Soil nitrogen reduction with time as a result of cultivation (adapted from Jenny, 1941).



Perhaps the subtle difference in perspective resulting from use of the term "restore" rather than "reclaim" has prompted a more holistic approach in the restoration arena. While we may appear overly critical, it is important to note that no papers in this symposium address soil microbiology or soil ecology, and only one of 34 papers addressed the topic at a recent symposium addressing "innovative approaches" to reclamation (Schaller and Sutton, 1987).

Miller (1984) reported that carbon-to-nitrogen and carbon-to-phosphorus ratios affect the establishment and maintenance of mycorrhizal populations in topsoil placed over reclaimed subsoils. Miller also noticed that stockpiling topsoil seriously impeded the mutually dependent processes of seed germination and mycorrhizae activity. This information, when compared with Keever's (1983) observations reminds us that we know very little of the important interactions between plant roots and their environments. In fact, Miller (1987) later stated that the discovery of the prevalence of mycorrhizal fungi in plant communities and the growing awareness of the roles played by mycorrhizae in the lives of plants was ". . . one of the most significant ecological events of the decade."

Among the observations about the role of mycorrhizae in reclaimed minesoils are Schramm's (1966) discovery that early ectomycorrhizal development was essential for seedling establishment of tree species on anthracite wastes in Pennsylvania. Only mycorrhizae inoculated seedlings survived. Later, Marx (1975) observed higher survival rates of inoculated pine seedlings than uninoculated seedlings planted on acid mine spoils. Indigenous mycorrhizae were more beneficial than introduced species.

Sopper and Seaker (1987) amended minesoils with sewage sludge as supplemental O.M. and planted tall fescue (*Festuca arundinacea*), orchardgrass (*Dactlylis glomerata*), and birdsfoot trefoil *Lotus coniculatus*). The sludge-amended soils produced higher percentages of forage cover and greater forage biomass than untreated controls. Large, diverse microbial populations accompanied the sludge treatments, but were absent in the controls. Soil organic matter levels generally increased with site age, but at a faster rate on sludge-treated sites. Earthworms were found only on five-year-old sludge treated sites, which were the sites with the greatest CO_2 evolution and the highest O.M. levels. Sopper and Seaker (1987) concluded that sludge application contributed to rapid revegetation and enhanced rejuvenation of microbial populations.

Very little research has investigated the role of earthworms, another important soil builder (Buntley and Papendick, 1960: Buol et al., 1980; Hole, 1981), in reclaimed soils. However, Vimmerstedt and Finney (1973) reported that on minespoil banks, earthworms buried or consumed the equivalent of 5 metric tons leaf litter ha^{-1}. In a 174 day greenhouse study, earthworms buried or consumed the equivalent of 9.5 metric tons of litter and 52.5 metric tons of humus while depositing on the soil surface the equivalent of 16.7 metric tons of castings. Infiltration and air permeability were significantly improved as a result (Vimmerstedt and Finney, 1973).

The holistic approach to the study of soil systems

The tendency of scientists to focus upon the parts of the system most closely related to their interests is not new. Only recently, with the growing awareness of global environmental issues has a systems approach to environmental issues been advocated. Wilding and Drees (1983) noted in their discussion of soil spatial variability that for several decades the focus of agricultural experimental designs was

> ". . . to interpret the significance of main treatment effects (yield or fertility response) with little or no effort to understand the results in terms of soil conditions. Variance due to soil parameters was extracted as blocking or replication. . ."

The perspective is shared by others, including Daniels and Hammer (1992) and Hammer (1991) who warned that any investigations of soils will be incomplete or unsatisfactory if the soils are not considered as parts of a dynamic system which includes an understanding of the abiotic factors causing coevolution of the soil-landscape and the adapted biota. Rowe (1984) noted that pedologists at some time became interested in soils as entities unto themselves, a problem whose solution he could not foresee until pedologists again recognize that soils are the "rooting medium and detritus component of ecosystems." Rowe was careful to state that the problem (of narrow vision) was not limited to pedologists. He explained that most earth-related sciences experienced their beginnings before ecology was defined. He said that

> ". . . because of that historical mistake, pedologists, phytosociologists, climatologists, animal ecologists and geomorphologists work diligently today in their separate fields, occasionally bumping into one another in the landscape ecosystems where periodically they go alone to get more material."

Rowe went on to say that the emerging discipline of landscape ecology offers the conceptual framework within which the disciplines can integrate with a common focus. However, existing landscape ecology treatises greatly understate the role of soils in the flow of energy, nutrients, and water in ecosystems (Naveh and Lieberman, 1984; Forman and Godron, 1986).

It should be noted that this symposium contains numerous examples of multidisciplinary approaches to obtaining higher crop yields from reclaimed minesoils. The magnitude of the mandated reclamation challenge has forced multidisciplinary work. The related realm of ecosystem restoration is also characterized by multidisciplinary approaches, although focus on ecological concepts is more strongly emphasized than is practiced by those responding to the agricultural challenges of prime farmland reclamation. Prime farmland reclamation will move closer to success when the reclaimed minesoil is approached from the perspective that it is a dynamic biological and physical system whose interface occurs where the plant root contacts the soil.

There are lessons to be learned from our colleagues in ecosystem restoration and in systematic ecology. Some key issues relating to restoring the soil have been addressed here. Bradshaw's comments are germane. He noted that to many people, particularly engineers, reclamation is not a biological issue, but is a technical, resource problem of finding permanent, economical ways to stabilize land surfaces and control pollution (Bradshaw,1987). Bradshaw is correct that this is an incomplete perspective, because land reclamation should strive to model the achievements of nature, and therefore must be based upon the lessons and examples nature has provided.

RECLAMATION CONSIDERATIONS FROM AN ECOLOGICAL PERSPECTIVE

Perspective one: Agronomic and soils rejuvenation vs. bond release

A paradox exists. The SMCRA requires that prime farmland be reclaimed to productive levels equal or greater to similar, unmined soils. The operator wants, for economic reasons, to obtain complete bond release as soon as possible. The ecological and pedological literature reveals that certain soil-building processes are accomplished in decades or centuries, and that traditional agricultural practices degrade rather than build soils. Is it realistic to expect that all soil systems can be restored to former levels of productivity within the six to 12 year window provided by the law? Clearly this is an issue that should be reviewed and evaluated. Soils vary regionally and locally. Is it reasonable to expect one law to pertain to all soil and climatic systems? Is it not reasonable to suggest that some soil systems should be restored to a condition compatible with local climate and parent materials, then be allowed to naturally regenerate prior to resuming cultivation? Another alternative could be to require that reclaimed minesoils be farmed with crop rotations shown to build or maintain soil O.M. levels. It would seem that any reclamation alternative which promotes soil improvement would be desirable.

Secondly, the regulations governing soil replacement are not flexible and may actually result in some less than desirable reclamation. For example, the subsoils across much of Missouri are acidic, but are underlain by unoxidized glacial till high in weatherable minerals. The till is better soil material than the subsoil. However, the review process required for each reclamation plan is lengthy and exhaustive. The operator is therefore encouraged by law to replace the soil as it was rather than to improve it by using the glacial till. The solution would be to review the soil replacement requirements for each site on an individual basis.

Perspective two: Is the concept of land use valid as perceived through the law?

The first example is alternative uses of reclaimed minesoils. Klimstra and Nawrot (1987) addressed this issue with vigor and an creativity. They lamented the legal pressure to return the land to its premined condition when other environmental concerns are of equal or greater importance. Wetlands construction as a part of surface mine reclamation was their focal point. Soil compaction, which impedes vertical water movement and root growth, is a primary reclamation problem. The reclamation process, by creating compaction, favors the development of water catchments (wetlands) in certain parts of the landscape. The potential benefits of wetlands are numerous, with obvious benefits for wildlife and recreation. At the same time that one federal government program encourages the maintenance and restoration of wetlands, a federal law restricts their construction on well-suited sites.

Much of Missouri is a natural ecotone between the eastern deciduous forest and the tall grass prairie biomes (Braun, 1950) and rainfall often is limiting in timing and abundance to create maximum crop yields. Why should law restrict the wetlands construction as a part of reclamation? Most farms in the area have farm ponds. Water for irrigation would improve the productivity of the reclaimed land in dry years. Irrigation is becoming a more common management practice in much of Missouri. We submit that wetlands, with the proper design, planning, and cooperation among agencies, would be economically effective, environmentally sound reclamation alternatives which would improve the agricultural production of reclaimed lands while providing additional, desirable alternative land uses.

A second issue is land use on minesites. Rather than reclassify each area of a permit as a particular land use, we submit that a better method would be to regulate the maximum slope of the entire minesite and allow an overall reclamation plan which recognizes that in unmined landscapes, soil properties vary among geomorphic surfaces. The concept of "land uses" requires the operator to submit volumnous amounts of paperwork when requesting changes. Region-specific landscape reclamation models are suggested to eliminate individual permits for each requested land use on a mine site. This would greatly reduce the volumes of paperwork required of the operator, hours of review by regulators, and would permit long-range planning based on landscape ecology concepts.

Perspective three: Ambiguous experimental practices regulations

Currently, variances may be submitted for the purposes of conducting experiments, for new research, and for creating alternative land uses. The applicable regulations are general, allowing the operator and the regulatory staff different interpretations of the same passages. Examples of such ambiguity are "... logically planned, implemented and monitored." Regulations require the operator to "conduct monitoring" and to "ensure the collection, analysis, and reporting of reliable data." Proposals generally require many iterations between regulator and operator, with much consumed time and energy. The result is that few experimental practices have been approved since Public Law 95-87. Although rapid advances are being made in many scientific disciplines, including soil microbiology, plant genetics, Geographic Information Systems, rhizosphere chemistry, and spatial statistics, current inertia prohibits or unnecessarily delays application of new knowledge. The experimental practices regulations are valuable and serve an important purpose. However, some streamlining is necessary to ensure timely, cost-effective application of new concepts.

A possible solution could be to require the operator to assume differing levels of liability for different experimental practices. The degree of liability could be correlated to degree of environmental risk. For example, a "Type I" experimental practice might require lengthy review and a high bond, while a "Type II" experimental practice might require little liability and brief review. If published, peer-reviewed research shows that power plant by-products are low-risk, potentially beneficial soil amendments in minesoil reclamation, the experimental practices review should allow rapid, controlled field verification.

SUMMARY

Growing public concern and awareness of the role of man in his environment will likely ensure that surface mining and other resource utilization activities will continue to be regulated by law. Existing laws have endured and probably will continue to do so. Surface mine reclamation has provided society with a unique situation. The theorist (research scientist), the agronomist, the engineer, the reclamation specialist, and the regulator have met at the mutual interface of their disciplines. All of the participants have learned much and experienced related, if not different frustrations. All share a common goal—learning to wisely and economically utilize our finite resources in such a way that the land we bequeath to our children and grandchildren will sustain them in health and happiness. We must work together to apply what we know in environmentally and economically sound ways. The keys to our successes lie in recognizing our mutually shared objectives and in approaching the reclaimed landscape as an ecological system in which the soil is the dynamic interface between the biotic and the abiotic components.

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Vegatation Productivity Equations: An Overview

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Abstract. Vegetation productivity equations are being reported by reclamation investigators. Present equations have been devised for predicting plant growth (woody plants, crops and rangeland) on reclaimed soils. Equations have been derived for Juniperus virginiana, Picea glauca densata, Picea pungens, Pinus ponderosa scopulorum, Celtis occidentalis, Fraxinus pennsylvanica, Populus deltoides, Salix alba tristis, Ulmus pumila, Caragana arborescens, Cornus sericea, Prunus americana, Prunus virginiana, Syringa vulgaris, sugarbeets (Beta vulgaris), spring wheat (Triticum aestivum, spring sown cultivars), oats (Avena sativa), barley (Hordeum vulgare), sunflowers (Helianthus annus), soybeans (Glycine max), and grasses-legumes. The equations employ soil hydraulic conductivity, percent slope, topographic position, bulk density, percent rock fragments, electrical conductivity, percent clay, and percent organic matter as predictors. The equations have R-square values ranging from 0.6 to 0.8, a p-value less than 0.0001 for the total regression, p-values of less than or equal to 0.0101 (Type II sums of squares) for each regressor.

Currently, the reported equations are limited to reclamation applications within Clay County, Minnesota and limited to soils derived from the same parent material as employed in the studies. Another study is currently developing equations for the coal fields of North Dakota. Unfortunately, the equations lack a theoretical/ecological framework to explain them; however, the equation approach is practical and applicable to reclaiming soils from a wide variety of disturbances including surface mining, construction activities, and landfills. In contrast to reference area reclamation verification methods, the equations can provide a quick, defensible, and statistical analysis of the suitability and capability of a soil profile to support plant growth. In some states, reclamation laws may require amendment to accommodate productivity equations as a legal method to verify soil ability to support plant growth.

Individuals can construct similar equations for their region or county providing there exists a suitable Soil Conservation Service soil survey(s).

INTRODUCTION

Reclamation research has led to the formative development of empirical prediction models to forecast the suitability of reconstructed soils (neo-sols) on reclaimed surface mines and other post-disturbance landscape conditions including reclaiming the landscape for prime farmland. This approach can aid in creating the optimum post-disturbance landscape configuration during the pre-site development and governmental permitting stages to generate usable landscapes for agriculture, forested lands, transportation corridors, naturalized vegetation associations, and urban vegetation applications. These equations may cause the current time consuming and expensive reclamation assessment methods such as reference evaluation procedures to become obsolete (Doll and Wollenhaupt 1985 describe the problems associated with reference areas). This paper describes the current body of knowledge associated with reclamation productivity equations and suggests future investigatory directions necessary to develop an increased understanding in predicting vegetation response to neo-sols.

LITERATURE REVIEW AND CURRENT RECLAMATION MODELS

Burley (1988) reviewed the historical development leading to the rise of predictive reclamation modeling as a tool to assist in pre/post-mining landscape planning and design. Significant early contributions leading to the development and issues concerning predictive reclamation equations include works by Neill (1979), Pierce, et al., (1983), Lohse, et al., (1985), Walsh (1985), Vories (1985), Doll and Wollenhaupt (1985) and Plotkin (1986).

Burley and Thomsen (1987) described a methodology to produce a quantitative reclamation productivity equation. The basis for this methodology originated with multivariate statistical concepts presented by

Kendall (1939), requiring computationally complex matrix algebra (see Johnson and Wichern 1988). With the advent of the computer to perform matrix algebra for dimensions greater than three, multivariate statistical techniques made reclamation productivity development possible. By computing eigenvalues and eigenvectors for all possible dependent variables such as crops and woody plants, an investigator could determine the extent of multi-variable covariance and develop an equation to represent a linear combination of variables to generate a single dependent variable. In other words, if the first eigenvalue was relatively large and the eigenvectors for the first eigenvalue were relatively similar, a simple equation derived from the eigenvectors (providing numerical weights for each crop type or woody plant type) would suggest a linear combination to combine the dependent variables into one value per soil type. With one dependent variable value per soil type, it was possible to perform multiple regression analysis upon one single dependent variable. Table 1 lists the vegetation types that have been employed by Burley and colleagues to generate dependent variables.

In the multiple regression analysis, a single independent variable value for each soil parameter was generated by applying a weighting formula suggested by Doll and Wollenhapt (1985), where the soil parameters in the first foot contributes 40% of a plant's vegetation production, the second foot in a soil profile contributes 30%, the third foot contributes 20%, the fourth foot contributes 10% and the remaining layers do not contribute to vegetation growth. With this formula, any soil parameter for a specific soil profile can be measured on a foot by foot basis (even inch by inch) and the investigator can generate a single value for each soil profile, such as a single weighted pH value or a single weighted bulk density value (see Burley and Thomsen 1987). Table 2 lists the variables employed by Burley and colleagues to generate independent variables.

It is also important to recall that most land-use disturbances do not typically affect some plant growth variables such as climate. Instead, disturbances associated with reclamation activities usually affect the soil. Thus in an equation, the analytic tool required is a measure to predict soil suitability. Some investigators have confused "real time crop-yield indexes" with reclamation productivity equations. While real time crop-yield equations can compute the predicted level of vegetation production for a particular year under specific field conditions experienced over the growing season, a reclamation productivity equation predicts the

Table 1. Dependent variables and units of measurement as recorded and published by the U.S. Soil Conservation Service (Jacobson 1982).

Abbreviation	CROP-WOODY PLANT	Measured Average Yield
JV	Juniperus virginiana	feet/20 years
PG	Picea glauca densata	feet/20 years
PP	Picea pungens	feet/20 years
PS	Pinus ponderosa scopulorum	feet/20 years
CO	Celtis occidentalis	feet/20 years
FP	Fraxinus pennsylvanica	feet/20 years
PD	Populus deltoides	feet/20 years
ST	Salix alba tristis	feet/20 years
UP	Ulmus pumila	feet/20 years
CA	Caragana arborescens	feet/20 years
CR	Cornus sericea	feet/20 years
PA	Prunus americana	feet/20 years
PV	Prunus virginiana	feet/20 years
SV	Syringa vulgaris	feet/20 years
SW	Spring Wheat	bushels/acre
BA	Barley	bushels/acre
OA	Oats	bushels/acre
SF	Sunflowers	pounds/acre
SB	Sugarbeets	tons/acre
SN	Soybeans	bushels/acre
GE	Grasses/Legumes	tons/acre

1 meter = 3.281 feet; 1 foot = 0.3048 meter

1 hectoliter = 2.837 U.S. bushels; 1 U.S. bushel = 0.363 hectoliter

1 hectare = 2.471 acres; 1 acre = 0.405 hectare

1 kilogram = 2.2046 pounds avoirdupois; 1 pound = 0.4536 kilogram

average expected yield across many years of cultivation. This average yield is produced by employing crop yield values that were measured over many years including drought years, wet years, warm growing seasons, and cold growing seasons. This averaging effect thereby negates the yearly variances upon crop yields produced by climate, allowing an investigator to study more closely the influences of soils upon vegetation growth over many growing seasons (see Burley and Thomsen 1987 for further elaboration).

Burley, Thomsen and Kenkel (1989) applied this mathematical approach to produce a productivity equation for seven agricultural crops: spring wheat, barley, oats, soybeans, sunflowers, sugarbeets, and grasses/legumes. The data base for this investigation was the Clay County soil survey (Jacobson 1982). The result was a reclamation productivity equation, Equation 1 (coefficient of multiple determination, 0.740).

Equation 1

PLANTS=.6206+(-1.1805*(HC-3.9296)/4.0030)+
(-0.3575*((SL-3.0000)/4.6810)**2)+
(-1.9375*((BD-1.3584)/0.2644)((FR-0.9075)/3.4929))+
(-2.3420*((EC-2.526)/1.0947)((FR-0.9075)/3.4929))+
(1.2424*((OM-3.9512)/0.6638)((EC-2.5269)/1.0947))

Where

PLANTS = Predicted Productivity Score
HC = Hydraulic Conductivity (inches/hour, 1 inch=2.54 cm)
BD = Moist Bulk Density (g/cm cubed)
FR = % Rock Fragments (percentage weight of particles > 7.62 cm)
EC = Electrical Conductivity (Mmhos/cm)
OM = % Organic Matter (percentage weight)
SL = % Slope
** Denotes raised to the exponent power.

Equation 1 does not consider woody plants and thus is not an all inclusive vegetation productivity model. Since reclamation often includes woody vegetation for the development of housing or commercial/industrial sites, wildlife habitat, agricultural shelterbelts, and forestry post-mining land-use applications, the development of a productivity model which includes woody plants would be more universally applicable in reclamation planning and design, including the development of prime farmland where woody plants composed of shelterbelts and windrows can be intricate components of an agricultural landscape.

Equation 2 is the selected best universal (universal in Clay County, Minnesota) reclamation equation derived from Burley's and Thomsen's (1987) methodology. The development of this equation was published by Burley (1991). The coefficient of multiple determi-

Equation 2

ALLPLANTS=.8916+(-1.4366*((HC-3.9296)/4.0030))+
(-1.1419*((SL-3.0000)/4.6810)((TP-2.575/0.9682)+
(-2.3041*((EC-2.526)/1.0947)((FR-0.9075)/3.4929))+
(-0.5887*((EC-2.526)/1.0947)((CL-22.843/14.3063))+
(-1.9375*((EC-2.526)/1.0947)((BD-1.3584)/0.2644))+
(1.2424*((OM-3.9512)/0.6638)((FR-0.9075)/3.4929))

Where

ALLPLANTS = Predicted Productivity Score
HC = Hydraulic Conductivity
SL = % Slope
TP = Topographic Position
BD = Bulk Density
FR = % Rock Fragments
EC = Electrical Conductivity
CL = % Clay
OM = % Organic Matter

Table 2. Main effect independent variables and units of measurements from the U.S. Soil Conservation Service (Jacobson 1982).

Abbreviation	Factor	Unit of Measurement
FR	% Rock Fragments	Proportion by weight of particles > 7.62 cm
CL	% Clay	Proportion by weight
BD	Bulk Density	Moist Bulk Density g/cm^3
HC	Hydraulic Conductivity	Inches/hour (1 inch=2.54 cm)
PH	Soil Reaction	pH
EC	Electrical Conductivity	Mmhos/cm
OM	% Organic Matter	Proportion by weight
AW	Available Water Holding Capacity	Inches/inch, cm/cm
TP	Topographic Position	Scale 1 to 5 Where: 1=Low (Bottomland) 2.5=Mid-slope 5=High(Ridgelines)
SL	% Slope	(Rise/Run)*100

nation in the equation is 0.795. In other words, the regressors explain approximately 80% of the variation in the regression model.

Burley (1990) also reported an equation (Equation 3) that described a sugarbeet model, because the eigenvalue and eigenvector interpretation reported by Burley (1988) suggested that although sugarbeets covaried with other crops, they may be significantly different to the extent that a "sugarbeet only model" merited investigation. The coefficient of multiple determination in the sugarbeet equation is 0.63.

Currently, Burley is reviewing soil reclamation assessment methods for several selected states in the United States of America (North Dakota, South Dakota, Minnesota, Wyoming, Indiana, and Michigan). Numerous states require quantitative reclamation assessment procedures (primarily for coal surface mining reclamation on prime farmlands), meaning that soil productivity equations are potentially compatible with these quantitative assessment demands and could make a contribution in evaluating the post-disturbance soil environment. Burley and Thomsen (1990) have described an approach employing a soil productivity equation for reclaiming surface mines.

While some soil scientists, foresters, agronomists, ecologists, and reclamation specialists may consider these formative equations noteworthy, the development of these equations is not without indirect criticism. For example, Power and Kareiva (1990:312-313) note, "All too often, researchers report significant effects but ignore the processes that lead to these effects." They also state that, "Such models are often so lacking in theoretical content that they do little to advance our understanding of how systems work."

Williams and Schuman (1987) provide one of the few attempts to integrate reclamation soil parameters with empirical equations and biological processes. Yet Power and Kareiva (1990:312) might counter that too many of these investigations are single factor studies or studies that consider the interactions of only a few variables.

Equation 3

SBP=-0.342+(0.339*(CL-22.84)/14.3)+
(0.425*(pH-7.50)/0.43)+
(0.182*((CL-22.84)*(CL-22.84)/14.31))+
(-0.816*((AW-0.259)/0.69)*((CL-22.84)/14.31))+
(0.363*((pH-7.50)/0.43)*((EC-2.53)/1.09))

Where

SBP = Sugarbeet Productivity (unitless)

CL = Percent Clay, by weight

pH = pH

AW = Available Water Holding Capacity, cm cm-1

EC = Electrical Conductivity, Mmhos cm-1

In addition to lacking a theoretical basis, including processes, to explain reclamation productivity equations, there seems to be a host of other fundamental criticisms applicable towards reclamation productivity equations (see Burley 1991). While no scholar has directly attacked these equations, the primary investigator who developed these productivity equations has compiled a list of shortcomings associated with reclamation productivity equations, meriting further investigation, including:

A. the need for self-validation analysis (bootstrap and jackknife statistical techniques),
B. inclusion of empirical data from reclaimed sites into the models,
C. the study of neo-sol long term productivity rates,
D. inclusion of toxic parameters into the models,
E. theoretical/biological/ecological basis for the equations.

Figure 1 illustrates these concerns and their relationship to reclamation productivity equations. The remaining text presented in this paper addresses each of these associated concerns separately.

DISCUSSION

Theoretical Basis

Developing a theoretical basis for explaining empirical results can be a difficult task. In scientific methodology approaches often presented in academia, few if any discussions, seminars, or coursework address, "how one might develop a theory from empirical information."

The equations developed by Burley et al appear to reflect the idea that vegetation responds to a multiplicity of soil parameters for a given agroecosystem. In addition, a broad spectrum of vegetation types covaried around a specific set of ideal environmental conditions, at least for vegetation grown in Clay County, Minnesota agroecosytems. In the future, these vegetation responses may lead to a theory that explains the equations and empirical observations.

Validation Modeling

The current productivity equations are comprised of small data sets with 80 cases, representing the eighty soil types found in Clay county, Minnesota. The equations derived from this small data set could be skewed by selected soil cases. Three techniques useful in examining these small data sets include "Jackknife Estimates," "Bootstrap Estimates," and "Subsampling Estimates" (Mathsoft 1988:73-80).

Jackknife estimates remove one case from the data set, then calculate the variables of interest (in this case the coefficients of the regressors, the p-values of the regressors, and the coefficient of determination for the equation) termed the jth pseudo-values. Then the case is returned to the data set and the j+1 case is removed. The means and the variance of the pseudo-values can be inspected for large differences. Small differences are interpreted to indicate that no one specific case (soil type) drastically affects the outcomes from the data set.

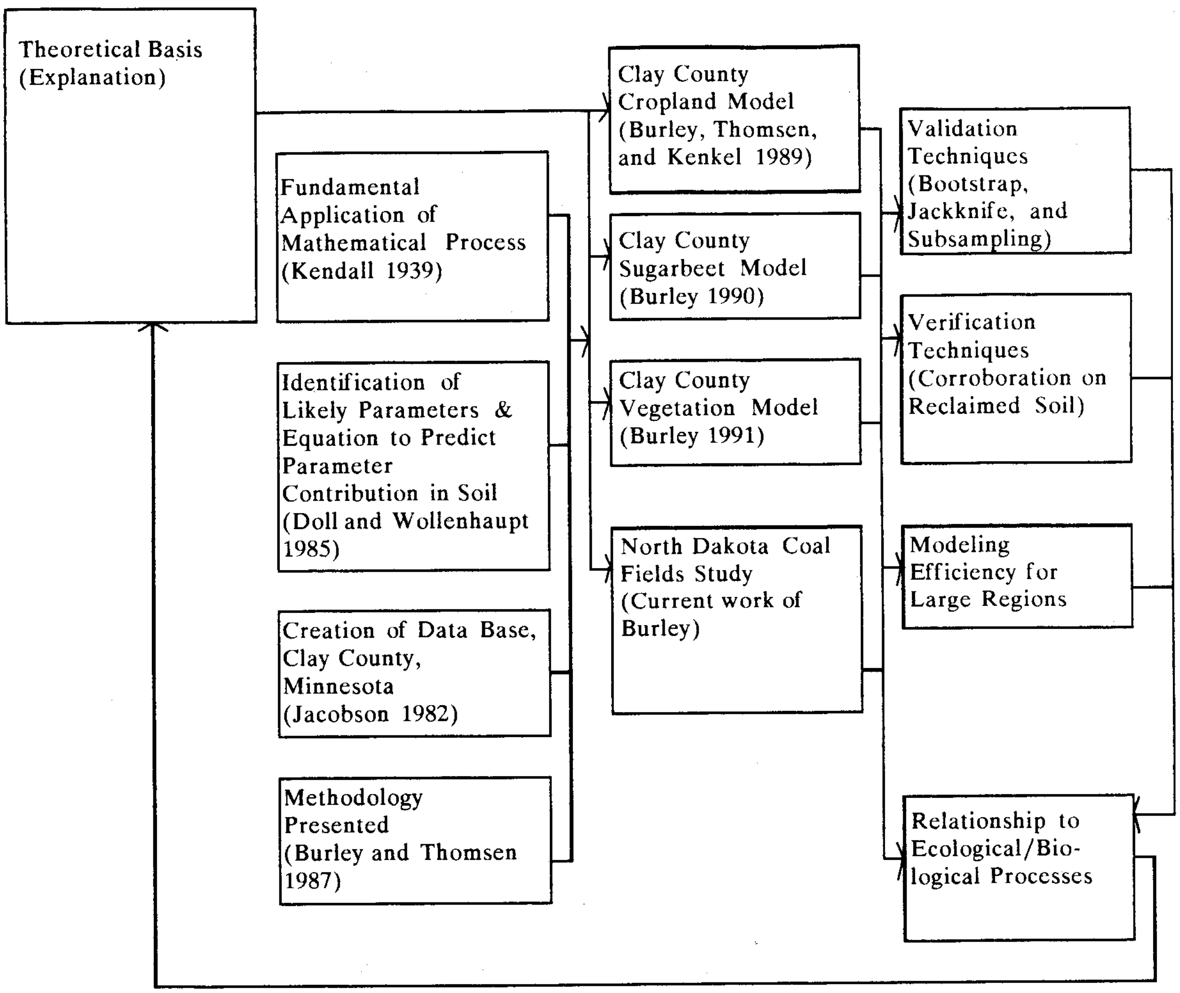
Bootstrap estimates randomly select a specified number of cases (such as 80) with replacement from the data set. Then the variables of interest are calculated. The random sample case selection is repeated a specified number of times (such as 100 or 200 times), generating a pseudo-sampling data set. The means and the variance of the pseudo-sampling data set are then computed. Again, small differences are interpreted to indicate that no one specific case (soil type) drastically affects the outcomes from the data set.

A third procedure would be to randomly select a subset of the cases, without replacement, then follow the equation procedures described by Burley and Thomsen (1987) with this subsample. The cases that were not selected would then be employed in the derived equation to examine existing productivity values with predicted productivity values. Comparisons with high correlations would indicate that the data set is not affected by selected cases (soil types). If there is not a high correlation, the data set is subject to strong influences by particular cases (soil types), indicating that the equation may not be as robust as previously suspected.

Post-disturbance Data Sets

Presently, the reclamation productivity equations presented by Burley and colleagues have been generated strictly from pre-mining soils. None of the soils employed in the studies have been from soils reclaimed

Figure 1. Flow-diagram illustrating the connections to existing work and related issues requiring further investigation.



in surface mining operations. The data sets have been derived from "pristine" soils. Thus, the claim that these equations are applicable to post-mining soils is without direct empirical evidence. The authors of these equations suggest that, providing that one uses the same overburden material derived from the eighty soil types, the equations may be a reasonable predictor. However, this claim is purely speculation. Until reclamation productivity equations use data supplied from post-mining soils (soil parameters and crop yield data), the reliability of these equations is still in doubt.

Long Term Reclamation Productivity

Reclamation productivity equations and long-term landscape neo-sol stability should be investigated to verify the suitability of various soil treatments suggested by the model. Burley (1988) notes that the stability of chemical and physical parameters in neo-sols has not yet been firmly verified. Neo-sols could remain stable, slowly become less productive, or actually improve over time. Predictive integral equations where time is introduced as a variable may be used as an approach to generate long term descriptions of soil productivity rates.

Toxic Conditions

There are numerous soil parameters that have not been introduced into the reclamation productivity modeling process. Soil parameters that encounter abnormal levels of selenium, boron, or sodium adsorption ratio (SAR) may be pertinent to the equation modeling process. The soils studied for Clay County, Minnesota were not necessarily toxic, meaning that no toxic variable was entered into the equation modeling process, as discussions with soil scientists for the region suggested that Clay county did not have any pertinent soil toxicity conditions for the eighty soils studied (see Jacobson 1982 for a description and classifcation of the soil profiles and series).

Ecological Processes

Ties to ecological processes through the reclamation productivity process have not been conducted. Although there may be numerous speculative arguments concerning the ties between ecological processes and reclamation productivity equations, little or no substantive work has been initiated. Some ecologists believe that connecting empirical equations to ecological processes is an important aspect in the development of scientific understanding.

SUMMARY REMARKS

Reclamation productivity equations are presently being reported (Burley, Thomsen, and Kenkel 1989, Burley 1990, and Burley 1991) for a particular county in Minnesota (Clay County), with a new investigation being conducted in North Dakota to test the methodology on a larger region. The North Dakota investigation will examine self-validation issues, reclaimed soil verification, and modeling efficiency for an area larger than one county.

Burley and colleagues suggest that the Minnesota equations are able to predict soil vegetation productivity values and compare means between predicted soil productivity values with 95 % confidence levels (Burley 1991). However, unless one is intending to reclaim sites in Clay County, Minnesota, the current equations are of only modest immediate and practical significance.

The equations may require further internal validity testing, the incorporation of cases from reclaimed soils, the addition of toxic soil parameters, and may eventually contain an integration function to predict changes in soil productivity over time.

Eventually, other investigators may adopt Burley and Thomsen's (1987) methodology to study the development of vegetation productivity equations for other regions.

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Evaluation of Small Grains on Minesoils

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Abstract. Yield response and tillering capacity of several soft red winter wheat cultivars grown on reclaimed surface mined lands to various seeding rates were evaluated over a two year period in southern Illinois. Two mine soils, one consisting of scraper placed rooting medium plus topsoil, and the other consisting of cross-pit wheel spoil plus topsoil were studied. Seeding rates were 60, 90, and 120 lb/a. An undisturbed tract of Stoy silt loam (Aquic Hapludalf) was used as an unmined comparison. Seeding rate significantly affected tiller numbers and grain yields on both mine soil treatments. No response to seeding rate was observed on the undisturbed Stoy soil. Results from this study indicate that higher seeding rates of soft red winter wheat are necessary on mined land to maximize productivity. Cultivars significantly affected grain yields on both the mined and unmined soils.

INTRODUCTION

Grain yield for wheat is a function of three parameters: i) the number of heads per unit area, ii) the number of seeds per head, and iii) the weight of the seeds. The number of heads per unit area can be affected by tillering capacity, seeding rate, row spacing, and environment. The tillering capacity of a specific cultivar can be extremely dependant upon environmental conditions and fertility levels. Since seeding rate and row spacing can be adjusted, several researchers in different locations have studied their effect on yield and yield parameters (Baker, 1982; Faris and DePauw, 1981; Guitard, et al., 1961; Johnson, et al. 1988; Joseph, et al., 1985; Marshall and Ohm, 1987; Roth, et al. 1984; and Tompkins, et al., 1991).

Approximately 1.5 million acres of soft red winter wheat is grown in Illinois annually. Most of the wheat is grown in the southern half of the state and a large percentage of the acres are double cropped with soybeans. Standard agronomic practices, cultivar selection, date of planting, seeding rate, row spacing, and fertility levels, have been developed for this geographical area; however, no information was available for mined soils in Illinois. Therefore, this study was designed to evaluate several soft red winter wheat cultivars planted at different seeding rates on mine soils in southern Illinois.

MATERIALS AND METHODS

Research was done on the Denmark Mine, Horse Creek Mine and a nonmined control site. All sites were located in Perry County, southwestern Illinois. The Denmark mine soil consisted of an area of scraped placed rooting media with 9 inches of topsoil replaced. The area had been tilled with the Kaeble-Gmeinder TLG-12 deep ripper. The Horse Creek mine soil consisted of cross-pit wheel spoil. A nearby tract of Stoy silt loam (Aquic Hapludalf) was used as the nonmined comparison in both years. The undisturbed soils of this region are formed on 4 to 6 feet of Peorian loess overlying Illinoian glacial till. Most of these soils have highly weathered acidic subsoils which are high in clay, highly plastic, and poorly aerated when wet. The C horizon consists of clacareous loess and calcareous glacial till and is chemically favorable for plant growth.

1988-89 Study: In the fall of 1988, three soft red winter wheat cultivars (Cardinal, Caldwell, and Dynasty) were planted on the Denmark mine and the nonmined control site. Plots were six-rows-wide with 7.0 inch row spacing and 25 feet long. Treatments were arranged in a randomized complete block design with six replications on the mined site and four replications on the nonmined site. Seeding rates were 60, 90 and 120 pounds/acre. All plots received 45 lbs/a of nitrogen fertilizer at planting and 45 lbs/a in the spring. The number of tillers/meter were determined at harvest on one of the center rows of each plot. Plots were machine harvested and grain weights were expressed as bu/a at 13.5% moisture.

1989-90 Study: In the fall of 1989, five cultivars (Cardinal, Dynasty, and Pioneer Brand 2550, 2548, and 2555) of soft red winter wheat were planted on the Horse Creek Mine, and on the nonmined Stoy site. Seeding rates were 90 lbs/acre and 180 lbs/acre for each cultivar. Plots were 21 feet wide and 200 feet long and treatments were arranged in a randomized complete block design with four replications. As in 1988-89, plots received 45 lbs/a of nitrogen at planting and again in the spring. Two subplots, 7.5 feet wide and 50 feet long, were harvested for each plot. Plots were machine harvested and grain weights were expressed as bu/a.

RESULTS AND DISCUSSION

1988-89 Study: Seeding rate significantly affected grain yields on the mine soil but no response to seeding rate occurred on the undisturbed Stoy soil (Table 1). Six replications were harvested on the mine soil in 1989 and four replications on the Stoy soil. Cultivars form the main treatment factor with seeding rate being a split effect. Cultivars significantly affected grain yields on both soils. Mean yields for cultivars and seeding rates are presented in Table 2. Yields for the Dynasty cultivar were the highest on both soil treat-

Table 2. Mean treatment yields of cultivars and seeding rates for the 1989 Denmark wheat experiment.

Treatment	Mine soil	Stoy soil
	----- Yield, bu/ac -----	
Cultivars:		
Dynasty	32.2 a	64.0 a
Cardinal	25.4 b	63.4 a
Caldwell	24.3 b	46.6 b
LSD (0.05)	2.2	7.3
Seeding Rates:		
1.0 bu/ac	23.2 c	57.7 a
1.5 bu/ac	27.7 b	58.5 a
2.0 bu/ac	31.0 a	57.7 a
LSD (0.05)	1.1	4.6
Target Yield-HCL[1]	41.8	

1/ Base target yields of high capability lands (HCL) for Denmark permit area calculated by IL Dep of Agric. This base target yield is adjusted annually by a county success factor to adjust for weather variation.

Table 1. Error mean squares and F ratios for cultivars and seeding rates on tillers/meter and grain yield at the Denmark mine and nonmined control site in 1988-89.

Source of Variation	df	Mine Soil Tillers	Mine Soil Yield	Stoy Soil Tillers	Stoy Soil Yield
		----- Mean Squares -----			
Cultivar (C)	2	33.40**	125.37**	21.43**	40.30**
Error a	15,9	3.76	9.37	4.41	6.25
Seed Rate(R)	2	11.33**	104.18**	1.17	0.10
R x C	4	2.31	1.70	0.99	0.04
Error b	53,35	2.25	2.61	5.22	29.20

**, Statistically significant at the 0.01 level.

Table 3. Tiller number and grain yields for seeding rates within cultivars for the three wheat cultivars in 1988-89 at Denmark mine and nonmined control sites.

Cultivar	Seeding Rate	Mine Soil Tillers	Mine Soil Yield	Stoy Soil Tillers	Stoy Soil Yield
	(lbs/a)	(no./m)	(bu/a)	(no./m)	(bu/a)
Caldwell	60	42.0	18.9	87.3	46.3
	90	58.3	24.6	82.0	46.5
	120	58.3	28.0	85.8	46.6
Cardinal	60	41.3	21.3	100.3	63.0
	90	59.3	25.0	102.0	64.5
	120	65.5	29.3	105.3	62.5
Dynasty	60	55.5	29.0	120.5	64.0
	90	64.8	30.9	118.8	63.6
	120	71.8	36.1	115.3	62.0
LSD (0.05)		5.3	2.7	6.8	9.3
Target Yield-HCL[1/]			41.8		

1/ Base target yields of high capability lands (HCL) for Denmark permit area calculated by Illinois Department of Agriculture. This base is adjusted annually by a county factor to adjust for weather variation.

ments. Caldwell cultivar yielded the lowest on both soil treatments. Cardinal yielded very well on the undisturbed Stoy soil but was significantly lower than Dynasty on the mine soil. Seeding rate had no effect on the Stoy in 1989, while seeding rate on the reclaimed soils did effect yield, and there appears to be a linear relationship that needs to be tested beyond the 2.0 bushel/acre rate. This response is probably due to reduced number of tillers produced on the mine soil treatment. In addition, the average number of heads per meter of row ranged from 40-75 for the reclaimed plots, while the number of heads on the Stoy soil ranged from 80-120 per meter of row. Response for seeding rates within cultivars are presented in Table 3.

1989-90 Study: There was a significant difference among the five cultivars on the Horse Creek mine soil and the nonmined Stoy soil in 1990 (Table 4). There also was a significant seeding rate effect at the Horse Creek location, and a significant R x C interaction at the nonmined site. This response is similar to the 1988-89 sudiies at the Denmark Mine, indicating a higher seeding rate is recommended on mined lands. Pioneer 2548 had the highest yields on both soil treatments when seeding rates were combined (Table 5). Pioneer 2550 had the second highest yield at Horse Creek, but it produced the lowest yields on the undisturbed Stoy site. This cultivar is an older cultivar that is reported to have "drought tolerance". Based on its performance in the mined plots, this appears to be correct. All five cultivars had higher yields at the 180 lb/a seeding rate than the 90 lb/a rate (Table 6 and Figure 1); however, the difference was not significant for individual cultivars. The significant seeding rate effect for the mined soils in Table 4 resulted when the two seeding rates were compared over all five cultivars. The mean grain yield over cultivars at the 90 and 180 lb/a seeding rates was 38.6 and 41.5 bu/a, respectively, with a LSD value (0.05) of 2.2 bu/a. There was a significant reduction in yield associated with the 180 lb/a seeding rate on the nonmined soils for Dynasty and Pioneer Brand 2550. Conversely, Cardinal had a significantly higher yield at the 180 lb/ a seeding rate and Pioneer Brands 2548 and 2555 were not affected.

SUMMARY AND CONCLUSION

Small grain yields on mined soils were significantly lower than the nonmined soils in both years. None of the cultivars equalled the target yield for Perry county in 1989. The lower yield on the mined soil was associated with fewer tillers compared with the nonmined soil and to increased sensitivity to weather stress on mined land.. In 1990, Pioneer Brand 2550 exceeded target yields at the 180 lb/a seeding rate. Pioneer Brand

Table 4. Error mean squares for the effect of cultivar and seeding rate on grain yield in 1990 at Horse Creek mined and a nonmined control site.

Treatment	df	Mine Soil	Stoy Soil
Cultivars (C)	4	503.3**	1289.8**
Error a	12	175.6	42.3
Seeding Rate (R)	1	171.7**	26.1
R x C	4	10.5	48.6**
Error b	52	24.1	8.9

**, Statistically significant at the 0.01 level.

Table 5. Mean treatment yields of cultivars and seeding rates for the 1990 wheat experiment.

Treatment	Mine Soil	Stoy Soil
	(bu/a)	(bu/a)
Cultivars:		
Pioneer 2548	48.6	66.6
Pioneer 2550	41.6	42.2
Cardinal	38.9	48.5
Dynasty	37.6	51.3
Pioneer 2555	33.5	52.3
LSD(0.05)	10.2	5.0
Seeding Rate:		
90 lb/acre	38.6	52.7
180 lb/acre	41.5	51.6
LSD(0.05)	2.2	1.4
Target Yield-HCL[1/]	41.8	

[1/] Base target yields of high capability lands (HCL) for Denmark permit area calculated by IL Dep of Agric. This base target yield is adjusted annually by a county success factor to adjust for weather variation.

Table 6. Grain yields for seeding rates within cultivars for five soft red winter wheat cultivars in 1990 from the Horse Creek mines and the nonmined control site.

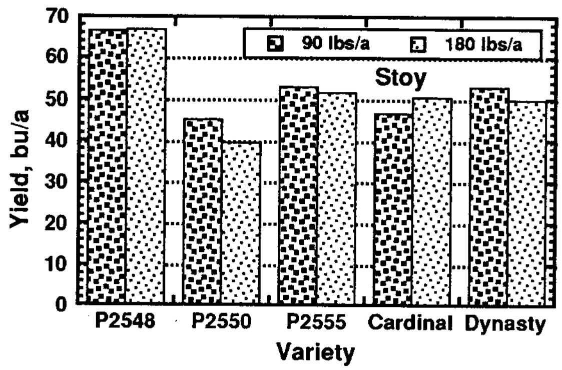
Cultivar	Seeding Rate	Mine Soil	Stoy Soil
	(lbs/a)	(bu/a)	(bu/a)
Cardinal	90	36.3	46.6
	180	41.6	50.4
Dynasty	90	36.6	53.0
	180	38.7	49.8
P2550[2]	90	40.1	44.9
	180	43.3	39.5
P2548[2]	90	47.1	66.4
	180	50.2	66.8
P2555[2]	90	33.1	53.0
	180	34.0	51.6
LSD (0.05)		9.3	2.7
Target Yield-HCL[1/]		41.8	

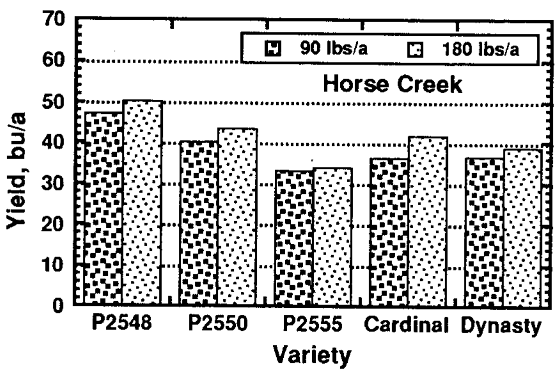
[1/] Base target yields of high capability lands (HCL) for Denmark permit area calculated by Illinois Department of Agriculture. This base is adjusted annually by a county factor to adjust for weather variation.

[2/] P2550, P2548, and P2555 are the designations for Pioneer Brand 2550, Pioneer Brand 2548, and Pioneer Brand 2555.

2548 exceeded the target yield at both seeding rates. The number of tillers wasn't determined in 1990. However, visual observations suggest there were fewer tillers at the lower seeding rate on the mine soil in 1990 as well. Yield data from both years indicate there are differences among the cultivars. Additional research is needed to develop recommendations for mined soils, but a seeding rate above the recommended 90 lb/a appears to increase yields on mined land.

Figure 1. Effect of seeding rate on 5 wheat varieties on mined and unmined soils in 1990.





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Corn Hybrids for Reclaimed Surface Mine Soils in Kentucky: Hybrid Performance Plus Maturity and Planting Date Evaluations

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Abstract. Agronomic performance of corn hybrids were evaluated for three years on reconstructed surface mine soil at the River Queen Mine in Kentucky. Means from the surface mine performance tests were compared to performance test results conducted on undisturbed soils. Within a year, hybrids in the two test types had similar harvest moistures but little correspondence of agronomic performance. Neither single nor multiple year data from the Kentucky Hybrid Corn Performance Test, performance evaluations conducted on undisturbed soils, were able to predict hybrid performance on reconstructed surface mine soils. Multiple year, but not single year, surface mine performance data provided a reasonable prediction of hybrid agronomic performance in a subsequent year's surface mine performance test. In a second experiment, four hybrids differing in maturity were planted at three planting dates. Full-season maturity hybrids and earlier planting date had the best agronomic performance on reconstructed surface mine soils at two Kentucky locations.

INTRODUCTION

Corn is produced in many different environments. Worldwide, corn is grown in tropical to temperate climates; from 40° south latitude to 58° north latitude; from below sea level to 13,000 feet altitude; in arid climates with as little as 8 inches of annual precipitation to areas with an excess of 100 inches of precipitation (Martin and Leonard, 1967). The extensive amount of genotypic variation available to corn breeders has been utilized to develop cultivars adapted to numerous environmental niches. Cultivars may differ in maturity, ability to withstand drought and heat, ability to resist diseases and insects, and in ability to recover nutrients from the soil. Hybrid varieties in the U.S. have been adapted to niches that are defined primarily by plant maturity relative to the growing season and to disease or insect resistances endemic to certain growing areas. In addition to specific adaptations for growing season and pest resistance, genotypic variation for productivity potential exists among hybrid varieties available from different seed companies. A corn grower in Kentucky or any other state must somehow make a choice among the tens or even hundreds of different hybrid cultivars made available to him by as many as 30 or more seed companies. The same decision faces the mine operator who plans to grow corn on reclaimed surface mine soils. A corn producer uses a number of guidelines in his selection of a hybrid(s). Information about hybrid adaptation, productivity, pest resistance, and other factors are presented by seed dealers. Recommendations based on experiences of fellow producers is often of value, but most grower decisions are made only after consultation of unbiased performance test data such as that provided by the state experiment station. The agricultural experiment station data is generally collected from numerous state environments that include different soil types and sometimes different production practices. The pertinent question for our interest is: Can the Kentucky Hybrid Corn Performance Test data (Evans and Poneleit, 1987; Poneleit and Evans, 1988, 1989, 1991a, 1991b) predict the performance of hybrids to be used on reclaimed surface-mined soils as well as it does for undisturbed Kentucky soils? Alternatively, must testing to determine hybrids suitable for reclaimed mine soils be done specifically on reclaimed surface mine soils? These questions will be examined in Experiment 1.

A second experiment will consider the time of planting and the interaction of hybrid maturity. Since both factors are known to influence corn yield potential, the influences of each will be studied in Experiment 2.

MATERIALS AND METHODS

Experiment 1

Forty - two hybrids were grown each year at the River Queen mine site in Ohio County, KY from 1987 to 1990. Most of the hybrids were selected from those grown in the Kentucky Hybrid Corn Performance Test

(KYHCPT) in the same year. Other hybrids, about 20 in 1988 and fewer in 1989 and 1990, were provided by the Illinois Prime Farmland Reclamation after Surface Mining research group as those that were expected to perform well under stress in Illinois tests. Three maturity check hybrids, FR27XLH38, FR27XMo17, and FR27XPa91, were included in both the tests on surface mined soils and in the KYHCPT. These maturity check hybrids were used to determine the environment x hybrid maturity interactions that might influence yield potential interpretations. The KYHCPT (Evans and Poneleit, 1987; Poneleit and Evans, 1988, 1989, 1991a, 1991b) were grown at seven Kentucky locations that represented most geographic areas of the state. One hundred thirty - two hybrids were grown at each test site. From 24 to 40 of the hybrids grown on the mined site were also included in the KYHCPT in any one year. The data from the state performance test in any year is the average over all seven locations. This seven site average is considered the best possible evaluation of hybrid performance potential. An attempt was also made to retain as many hybrids as possible from the prior years' surface mine test in the subsequent years' test on the surface mine site. From 26 to 30 hybrids were represented in subsequent tests and from 16 to 22 hybrids were represented in two or three year surface mine test averages.

Fertility, herbicides, insecticides, and tillage methods for the River Queen test sites were applied as per the recommendations of the Kentucky Cooperative Extension Service Recommendations in AGR-1 (Ananymous, 1990). Planting dates were as early as conveniently possible and ranged from late April to mid May. Fertility and other management inputs for the KYHCPT locations were applied for optimum production as recommended by the Kentucky Cooperative Extension Service. Planting dates ranged from late April to mid or late May. Planting of all plots was by use of a commercially available no-till planter modified with cone hoppers to facilitate plot size rows. All plots were two rows 36 inches apart and 22 feet long. All plots were planted with a set number of kernels to provide a planting density of 23,460 plants per acre. An additional 10% were planted in no-till plots. Plots were not thinned and stands at harvest were usually from 75 to 85% of the planted density. Grain harvest was completed with use of a small plot combine. Moisture content as well as grain weight was measured from each plot at harvest. All yields were calculated as bushels per acre at 15.5% moisture and 56 lb test weight.

All data were analyzed by Analysis of Variance (ANOVA) procedures for randomized complete blocks or lattices designs as appropriate. When the F test was significant, Least Significant Difference (LSD) statistics were calculated at the 0.10 level. Spearman rank correlations (SAS Institute, Inc.) were calculated for analyses of the predictive value for annual and multiple year means.

Experiment 2

Four hybrid varieties with a maturity range from 115 to 136 days were obtained from Pioneer Hybrid, Inc. The hybrids, Pioneer Brand 3475, Pioneer Brand 3378, Pioneer Brand 3320, and Pioneer Brand 3165 had harvest maturities of 115, 120, 130, and 136 days, respectively. The hybrids were planted on three dates in each year at two mine sites (Alston and River Queen) from 1989 to 1991 but only at River Queen in 1988. Planting was begun at the earliest time permitted by soil conditions and temperature. Subsequent plantings were attempted at about 10 day intervals. Planting dates were main plots and hybrid varieties were subplots. Cultural and management factors were as described above.

RESULTS AND DISCUSSION

Experiment 1

Average annual yield and moisture data for each surface mine test and KYHCPT are shown in Table 1. Within any one year, the average yield of hybrids in the surface mine test was less than the same hybrids averaged over seven locations of the KYHCPT. Harvest moisture content was about equal for the two test types in 1987 but was lower in the surface mine tests in all other years. Significant differences were found among hybrids in each test type in each year. The LSDs for the surface mine tests were always considerably higher than that of the KYHCPT because one location of data is being compared to seven locations of data.

Correlations among annual and multiple year means for yield and harvest moisture content are shown in Table 2. Several types of comparisons are made. Performance of the hybrids in the seven locations of the

Table 1. Average annual yield (bu/ac) and harvest moisture content (percent of wet weight) for surface mine and Kentucky Hybrid Corn Performance Tests grown in 1987, 1988, 1989, and 1990.

	Surface mine		Hybrid corn performance test	
Year	Yield	%moisture	Yield	%moisture
1987	83.0	15.5	156.8	15.2
1988	72.9	17.8	97.5	19.1
1989	101.7	16.1	152.5	19.8
1990	49.3	20.4	117.7	23.3

KYHCPT was compared on an annual basis with performance in surface mine tests conducted in the same year (comparisons 1-4). In only one case, in 1988, was the correlation between the two tests significant. The R^2 for this relationship was 0.17, which suggests minimal correspondence of variability in the surface mine environment with the variability arising from the average environment of tests grown in undisturbed soils. Similar comparisons for harvest moisture content show positive correlations in each year with R^2 values ranging from 0.27 to 0.55. Apparently the year environmental factors that control harvest moisture of the grain are more uniform over the growing area than are factors that influence yield.

In a predictive comparison, KYHCPT results would have been valuable to choose the top performing hybrids in the following year's surface mine test only when 1987 KYHCPT data were used to predict 1988 surface mine performance (Table 2, comparisons 5-7). Harvest moisture content from one KYHCPT year was no more accurate as a predictor of the following years' surface mine harvest moistures. Apparently both yield and moisture content can differ significantly from a year of KYHCPT to the following years' surface mine performance. Occasional correspondences may occur but our data do not indicate a consistent predictive relationship.

Two-year or three-year average data from the KYHCPT did not improve the predictive value of KYHCPT data for performance in surface mine conditions over the one year's performance test data for either yield or moisture content (Table 2, comparisons 8-10). Similar comparisons of KYHCPT data as a predictor of future performance on undisturbed soils in Kentucky are much different (Table 2, comparisons 11 and 12). In 1991, for example, the two-year yield mean of 1989 and 1990 was strongly correlated with 1991 yield ($r = 0.92$, $R^2 = 0.85$). The three-year yield mean of 1988, 1989, and 1990 was also strongly correlated with 1991 yield ($r = 0.74$, $R^2 = 0.54$). Comparable statistics for harvest moisture content are both $r = 0.83$, $R^2 = 0.69$.

Prior year surface mine performance tests also were ineffective as predictors of the following years hybrid performance for yield (Table 2, comparisons 13-15). Correlations were very low, ranging from -0.03 to 0.01. Correlations for harvest moisture were substan-

Table 2. Spearman rank correlations as indicators of predictability of hybrid performance on reclaimed surface mine soils by data collected from Kentucky Hybrid Corn Performance Tests (HCPT) on undisturbed soils and from data collected in prior year(s) surface mine performance tests (SM).

	- - - - - - - - - Data Set - - - - - - - - -			- - - - - Correlations - - - - -	
Comparison	Predictor	Predicted	N	Bu/ac	Percent Moisture
1	HCPT 1987	SM 1987	40	0.19	0.58**
2	HCPT 1988	SM 1988	25	0.42*	0.67**
3	HCPT 1989	SM 1989	27	0.12	0.52**
4	HCPT 1990	SM 1990	24	-0.04	0.74**
5	HCPT 1987	SM 1988	29	0.53**	0.25
6	HCPT 1988	SM 1989	18	0.38	0.44
7	HCPT 1989	SM 1990	30	0.03	0.60**
8	HCPT 1987-88	SM 1989	16	0.38	0.37
9	HCPT 1988-89	SM 1990	18	0.17	0.45
10	HCPT 1987-89	SM 1990	16	0.27	0.42
11	HCPT 1989-90	HCPT 1991	70	0.92**	0.83**
12	HCPT 1988-90	HCPT 1991	46	0.73**	0.83**
13	SM 1987	SM 1988	29	0.00	0.42*
14	SM 1988	SM 1989	26	0.01	0.15
15	SM 1989	SM 1990	30	-0.03	0.22
16	SM 1987-88	SM 1989	16	0.32	0.09
17	SM 1988-89	SM 1990	22	0.56**	0.15
18	SM 1987-89	SM 1990	16	0.53**	0.36

* Significant at $P \leq 0.95$

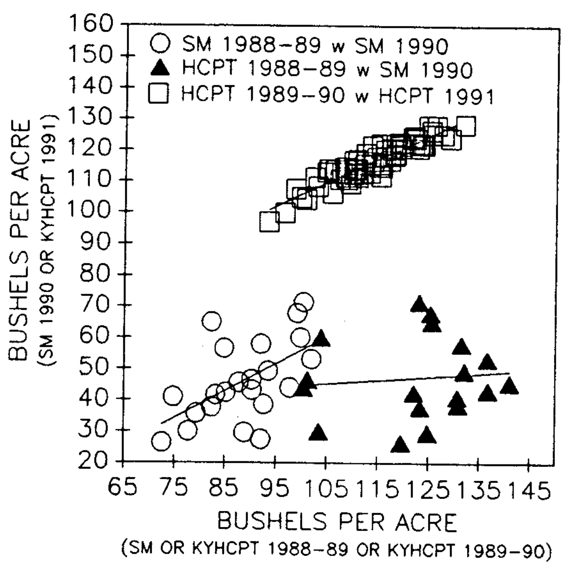
** Significant at $P \leq 0.99$

tially larger, but only one comparison, 1987 with 1988, was significant and explained only a small portion of the variation ($R^2 = 0.18$).

Predictive value of two- or three-year surface mine yield performance data was much better than for annual data (Table 2, comparisons 16-17). The correlation coefficients were significant for the two-year average, 1988 and 1989, and the three-year average, 1987, 1988, and 1989) with the 1990 surface mine yield performance. The two- and three-year variations explained a major portion of the 1990 variability; $R^2 = 0.31$ and $R^2 = 0.28$, respectively.

Although the magnitude of correlation data for the multiple year surface mine performance with a following year annual performance did not equal that for multiple year KYHCPT performance with a following year KYHCPT performance, the values were respectable considering that the surface mine data represented only one location per year while the KYHCPT data represented 7 locations per year. The use of multiple year surface mine yield performance data is, however, a better predictor of annual hybrid performance in a surface mine area than is multiple year data from undisturbed soils (Table 2 and Figure 1). The predictability of performance on reclaimed surface mine soil could be improved by including more hybrid observations per location and additional test locations. Larger numbers of hybrid observations (132 per year) averaged over seven locations for two years for KYHCPT data on

Figure 1. Plots of 2-year (1988 and 1989) surface mine (SM) and Hybrid Corn Performance Test (HCPT) data with 1-year (1990) SM data, plus 2-year (1989 and 1990) HCPT data with 1-year (1991) HCPT data.



undisturbed soils, provided much better predictability (Figure 1). Predictability of harvest moisture content in the surface mine tests was not improved by multiple year averages.

In summary for Experiment 1, hybrid performance on reclaimed mine soils is quite erratic from year to year. A feasible explanation for the variability is the extreme stress imposed on the corn hybrids by the disturbed soils. The fact that reclaimed soils often have less well developed soil structures, are more compacted, and have lower soil organic matter contents, as a result of the mixing of A and B horizons during reconstruction, could contribute to low moisture retention. Droughty conditions or precipitation as thunderstorms, instead of soaking rains, could accentuate the stressful conditions. In addition, stand establishment was poor in some years. Although stand data are not reported here, low stands did contributed to erratic yields; i.e. in 1990 two of the four test replications were discarded because of poor stands. In this case, the poor stands were partially the result of poor weed, control but mice and vole feeding was believed to have caused much of the stand loss.

In each year, however, some hybrids yielded enough to exceed the level needed for bond release. The low year to year correlations suggest that the same hybrids did not always perform well in successive years. Nevertheless, multiple year averages provided a substantially better yield performance prediction. Improved hybrid selection for yield should be possible if additional years (and locations) of testing can be provided.

Harvest moisture content for corn hybrids grown on reclaimed soils seems to be strongly influenced by the yearly weather. Most of the hybrids grown in the surface mine tests, except for the three maturity checks, were of similar maturities and weather influences apparently caused random variation of harvest moisture contents. Predictability of harvest moisture content was very low. Maturity check hybrid comparisons are evaluated later.

Experiment 2

In addition to the plot data originally planned to study the hybrid maturity/planting date interaction objective of Experiment 2, data of the maturity check hybrids from Experiment 1 is also considered here. Data from four years' tests on the maturity check hybrids in Experiment 1 are shown in Table 3. The yields of the early-season, FR27xLH38; mid-season, FR27xMo17; and full-season hybrids, FR27xPa91, increase from the early to the full season hybrid. The genetic control for maturity is confounded with genetic yield potential, but the general yield trend and harvest moisture trends were as expected. Both harvest moisture and yield increased with longer maturity (Table 3). In 1987 and 1989, the full-season hybrid yielded less than the mid-season hybrid, which is likely due to late season droughts that affected the full-season hybrid more than the mid-season hybrid in those years. The late drought effect is shown dramatically in 1989 harvest moisture data where the early- and late-season hybrids had nearly the same harvest moistures. The 1987 KYHCPT harvest moistures reflect the very early maturity in that year since each hybrid had very low harvest moisture and the difference between the late- and early-season hybrids was less than the average difference for four year data.

These data show that the full season hybrid did not express its true, higher yield potential in two of the four test years. The effect was less obvious for tests grown in undisturbed soils which would suggest less late season stresses in undisturbed soils. Extrapolating these results to the general case, later maturing hybrids may be at a disadvantage in disturbed soils in that effects of drought are more likely to occur late in the season on this soil type and in this geographic area. Alternatively, the highest possible yields will usually be associated with a full-season hybrid. The latter conclusion is derived primarily from HCPT tests on non-disturbed soils. Surface mine tests confirmed this conclusion in two years of four.

Planting date and hybrid maturity interactions were examined in Experiment 2. Four Pioneer Brand hybrids were planted at two surface mine sites in Kentucky at three dates in 1988 to 1991. Although 10 days was the intended interval between planting dates, soil or weather conditions made strict compliance impossible. Actual planting dates are shown in Table 4. Data from two locations/years were not included since deer feeding caused damage at River Queen in 1990 and poor stands reduced yield potentials at Alston in 1991.

The effect of hybrid maturity agrees with the conclusion from previous paragraphs, in that hybrids with later maturity generally outyielded earlier hybrids. This conclusion is shown in the yield average over locations and years and is statistically significant in nearly all individual location-year comparisons where significant

Table 3. Yields of maturity check hybrids from surface mine (SM) and Kentucky Hybrid Corn Performance Test (HCPT).

Year	Test	FR27 xLH38	FR27 xMo17	FR27 xPa91	Year Ave.	FR27 xLH38	FR27 xMo17	FR27 xPa91	Year Ave.
		bu ac^{-1}				% Moisture			
1987	SM	64.4b*	90.7a	66.5b	73.9	11.9c	15.4b	18.2a	15.2
	HCPT	138.0b	159.6a	165.0a	154.2	13.9b	14.4b	15.8a	14.7
1988	SM	62.6b	68.4b	97.2a	76.1	16.5b	16.8b	18.4a	17.2
	HCPT	78.5b	89.4a	97.4a	88.4	17.5b	17.6b	19.9a	18.3
1989	SM	92.8a	109.2a	89.6a	97.2	16.9a	15.7b	16.3ab	16.3
	HCPT	128.5b	160.2a	166.7a	151.8	18.0c	19.4b	21.2a	19.5
1990	SM	30.0a	29.6a	49.3a	36.3	16.1b	20.6ab	23.3a	20.0
	HCPT	102.1b	119.1a	117.3a	119.3	19.5c	21.9b	24.7a	22.0
Hybrid	SM	62.4	74.5	75.6		15.7	17.1	19.0	
Ave.	HCPT	111.8	132.1	136.6		17.2	18.3	20.4	

* Means in a row and for a variable, except for year or hybrid averages, followed by the same letter are not statistically different at $P \leq 0.10$

Table 4. Planting dates for Experiment 2 at River Queen (RQ) and Alston reclaimed surface mine sites.

1988	1989		1990		1991	
RQ	RQ	Alston	RQ	Alston	RQ	Alston
May 10	May 3	Apr 28	May 9	May 11	May 1	May 2
May 20	May 16	May 12	May 23	May 24	May 31	May 16
May 30	May 26	June 22	June 4	June 6	June 7	June 6

differences were observed (Table 5). Planting date had little influence on the relative performance of the four hybrids. Although an earlier hybrid was statistically equal to the latest hybrid in several planting date comparisons and no differences were shown among hybrids in other planting date comparisons, the average yield of the latest maturing hybrid was always highest. These data indicate that a full-season hybrid is generally the best choice for highest yield, but an earlier hybrid may, on occasion, provide an equivalent yield performance.

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SAS Institute Inc., SAS Circle, Box 8000, Cary, NC 27511.

Table 5. Grain yield (bu/ac) of four corn hybrids differing in maturity and planted at three different times at River Queen (RQ) and Alston reclaimed surface mine sites.

Pioneer Brand Hybrid	1988 RQ	1989 RQ	1989 Alston	1990 Alston	1991 RQ	Ave.
			Early planting date			
3475	29.3c*	66.3c	78.0b	71.4c	68.0	62.6
3378	43.1c	55.3c	89.2ab	88.3b	87.3	72.6
3320	77.8b	98.4a	83.9b	91.0b	70.1	84.2
3165	91.0a	89.0ab	114.0a	107.6a	68.9	94.1
			Intermediate planting date			
3475	52.7c	55.8c	116.0	75.3	71.5	74.3
3378	80.9b	59.2c	119.0	78.1	78.5	83.1
3320	90.4b	85.1b	104.0	89.8	69.4	87.7
3165	101.3a	104.0a	116.5	84.4	56.7	92.6
			Late planting date			
3475	83.3b	56.3b	86.2	72.3	80.1	75.6
3378	104.4b	36.0b	108.5	84.3	64.8	79.6
3320	118.5b	83.9a	87.2	65.0**	64.3	83.8
3165	120.5a	82.0a	112.3	95.6	46.6	90.8

* Means in a column within a planting date followed by the same letter are not significantly different at $P \leq 0.05$.
**Yield reduced by deer.

Corn Hybrid Responses to Mined Land in Illinois

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Abstract. A wide range of corn (Zea mays L.) genotypes were grown from 1988-90 at two mined land locations in western and southern Illinois. The southern Illinois site consisted of a scraper placed mine soil, while the western Illinois site was reclaimed using a cross-pit bucket wheel excavator. Nearby undisturbed soils were used as unmined comparisons. Results from these studies indicate that the potential to minimize the effects of stress exists through the selection of adapted genotypes. Hybrids with the highest yield potential on undisturbed soils did not necessarily produce the highest yields on disturbed soil plots. Weather variables were associated with yield variation more on the mine soils than on the undisturbed soil treatments. Hybrids grown on the mine soils built with scrapers, a high traffic system, yielded substantially lower than hybrids grown on the wheel spoil. This is due to differences in both the quality of pre-mine soil materials and the subsequent levels of soil compaction after reconstruction.

INTRODUCTION

Obtaining optimum row crop productivity on reconstructed mine soils requires the understanding of complex integrated soil, water, climatic, and genetic relationships. Crop varieties, plant populations, herbicides, and fertilizer rates are management factors that are generally recognized as affecting crop yields. The effects of these management factors are compounded when row crops are grown on newly constructed mine soils, which may have wide ranging physical and chemical properties, making it difficult to project productivity success. Because mine soils are fundamentally different from natural soils and have unique problems contributing to stress susceptibility of present commercial hybrids, the potential to minimize effects caused by the physical or chemical properties of mine soils should exist through hybrid selection. Corn yields of current commercial hybrids display considerable year to year variation when grown on mined land (Dunker and Jansen, 1987). There have been significant yield differences among soil reconstruction treatments in most years for an individual hybrid, but the ranking of treatments has not been consistent from year to year.

Genotype variation in response to environmental stress factors such as drought and heat stress has been observed in many fields (Blum, 1974; Boyer, 1970; Dedio, 1975; Sammons et al., 1978). Hyne and Brunson (1940) observed that corn hybrids showed less yield reduction under adverse drought and temperature stress than their inbred parents. Differences among hybrids in response to stress have been reported, with older hybrids generally affected more than newer genotypes. Russell (1977) concluded, after studying historically important hybrids, that genes for stress tolerance had been added to hybrids over years. Because the response of plants to drought, temperature, physical, and chemical stresses involves genotype X environment interactions, one needs to obtain, identify, and measure responses of various genotypes to distinguish those that respond in both favorable and unfavorable environments.

This cooperative study between the University of Illinois and University of Kentucky was initiated in 1988 to evaluate a wide range of genotypes on mined lands, compared to those growing on nearby natural soils. This study compliments work previously done in western Illinois (Dunker et al., 1988) and western Kentucky (Powell, et al., 1988).

MATERIALS AND METHODS

University of Illinois and University of Kentucky researchers managed the respective hybrid studies of their state. Common genotypes were included in each study to evaluate their performance over a wider range of soil and climatic conditions. The Illinois experiment is being conducted at two locations. The first location is at the Denmark Mine, Arch of Illinois Inc., in Perry County in southwestern Illinois. This mined land consists of an area of scraper placed rooting medium that has had topsoil replaced. An additional treatment involved the use of a Kaeble-Gmeinder TLG-12 deep ripper, which was used on one half of the mine soil area. Two nearby undisturbed soils, a Cisne soil (Mollic Albaqualf) and a Stoy soil (Acquic Hapludalf) were used as unmined comparisons.

The second site is located at Industry Mine, Freeman United Coal Company, in McDonough County in west-central Illinois. This experiment was initiated in 1989. One mine soil treatment, consisting of cross-pit wheel spoil with topsoil, and an undisturbed Keomah (Aeric Ochraqualf) were evaluated for hybrid response. As opposed to the scraper operation which can effectively segregate the various layers of unconsolidated materials, the mining wheel blends materials from the various layers of unconsolidated materials from the geologic column. Consequently the wheel spoil at Industry is a mixture of leached loess, calcareous loess, and glacial tills from the premine soils.

Soils formed the main treatment factor, while hybrids were a split effect, with hybrids randomly blocked (four replications) within each soil treatment. A John Deere Maxi Merge planter modified with cone seeder attachments for small plot use was used to plant hybrids. The two-row hybrid plots, 30 ft in length with rows spaced 30" apart, bordered with each other within the soil blocks so little border effect would occur. Planting population was uniform across hybrids at a rate of 23,500 seeds per acre. Management practices were similar to that of a typical farming operation. Hybrids were selected for this study based on current or previous use within the geographical area. The germplasm represents a wide range of characteristics with some experimental lines supplied by plant breeders interested in the response of these hybrids when grown on mined land.

RESULTS AND DISCUSSION

Denmark Mine

1988 Results

The Denmark hybrid plots were planted on May 11 under dry soil conditions. Emergence was slow and erratic as drought conditions continued through the month of May and into June. Severe early season stress was observed on all the soil treatments, although stress was most severe on the mine soils. Total rainfall for the month of June was only 1.7 inches, and was coupled with above normal temperatures. 1988 monthly rainfall totals were below normal in May, June, and August. The average maximum temperatures for June, July, and August exceeded 90 degrees F. The hybrid plots were helped by the late July rains which occurred at anthesis. There is no doubt, however, that corn yields were significantly affected by weather stress in 1988.

Results show that there were significant yield differences for both soil treatments and hybrids in 1988 (Table 1). There was a significant soil treatment by hybrid interaction indicating that hybrids were affected differently by soil treatment effects. Mean yields for the undisturbed Cisne and Stoy were significantly higher than either mine soils in 1988. There also was a significant response to the TLG deep tillage treatment on the mine soil area. There were significant differences among hybrids within soils for all four soil treatments (Table 2).

1989 Results

The hybrid plots were planted on May 18 under favorable moisture conditions following pre-plant incorporation of fertilizer and herbicides. An early season application of Roundup on April 26 was required to control perennial weeds and migrating thistle. Subsequent rainfalls aided emergence and below normal temperatures prevailed during this period. Emergence was variable among treatments with the No TLG treatment having the slowest emergence. Below normal precipitation and above normal temperatures occurred in late June and early July. While rainfall totals for the months of June and July were above normal, rainfall came in two major events during mid-July. Stress symptoms first appeared on the No TLG treatment, followed by the TLG and Stoy soil. The Cisne soil showed stress symptoms approximately one week later than the other treatments. The rainfall in mid-July aided pollination, but high temperatures and below normal rainfall in late July to mid-August further separated treatment differences.

Table 1. Mean squares and level of significance for the various effects in the analysis of variance for 1988 hybrid yield at the Denmark Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	3	65918.90**
Error (a)	12	1551.93
Hybrid (H)	19	1183.99**
S x H	57	486.48**
Error (b)	228	283.44

**, Significant at the 0.01 level of probability.

Results of the analysis of variance show there were significant yield differences for both soil treatments and hybrids in 1989 (Table 3). Yields from the Cisne soil were significantly higher than other treatments. Yields of the TLG and Stoy soil treatments were not significantly different, but yields on the No TLG treatment were significantly lower than any other soil treatment. Significant differences among hybrids within soils occurred on all four soil treatments in 1989 (Table 4).

1990 Results

Excessive spring rainfall prevented the planting of this experiment in 1990. Soils on the experimental plot areas remained in a saturated condition until late June. Most hybrids in this experiment are in a maturity range that would not respond to such a late planting date. A smaller number (5) of very early maturing hybrids were planted on the Lorsban 15G experiments on the Captain and Horse Creek mines. Results of hybrid response at these locations are discussed in that section of this report.

1988-89 Mean Yields

Two-year-mean yields for this study show the yields for the genotypes to be superior on the undisturbed Cisne soil (Table 5). Hybrid yields on the Stoy soil also were significantly higher than the two mine soils but, lower than the Cisne soil. Analysis of variance for two-year-mean yields show significant differences for both soil and hybrids. Significant hybrid by year and hybrid by soil treatment interactions indicate hybrids responded differently to year effects (environment) and for soil effects (Table 6). Two-year-mean yields for the 17

Table 3. Mean squares and level of significance for the various effects in the analysis of variance for 1989 hybrid yield at the Denamrk Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	3	113622.34**
Error (a)	12	521.91
Hybrid (H)	19	660.20**
S x H	57	383.03
Error (b)	228	345.82

**, Significant at the 0.01 level of probability.

Table 2. Ranking of hybrids by yield for the 1988 Denmark Hybrid Study.

Genotype	Cisne		Stoy		Scraper-TLG		Scraper-No TLG	
	bu/a	rank	bu/a	rank	bu/a	rank	bu/a	rank
Pioneer 3165	117	1	90	1	34	18	43	3
Asgrow 2570	115	2	69	8	49	11	35	7
LH123 x LH93	114	3	86	2	65	2	46	2
FR27 x Mo17	112	4	75	4	33	19	11	19
Pioneer 3320	109	5	74	6	48	12	20	17
Zimmerman Z28	108	6	74	5	52	10	38	6
Pioneer 3295	107	7	57	17	58	6	33	10
FR303 x RSC204	105	8	79	3	58	7	5	20
LH119 x LH51	104	9	63	14	45	14	20	16
LH132 x LH123	100	10	64	12	55	9	49	1
B73 x Pa91	97	11	68	9	45	15	14	18
LH136 x LH123	96	12	68	10	61	5	41	4
B73 x LH38	95	13	69	7	74	1	34	9
Pioneer 3377	94	14	62	15	62	4	40	5
LH74 x LH123	91	15	64	13	56	8	22	14
GRE 82-10	89	16	68	11	40	17	32	11
LH119 x LH82	86	17	56	18	45	13	34	8
B73 x BS10	76	18	38	20	27	20	21	15
LH74 x LH51	73	19	59	16	45	16	24	13
LH82 x LH146	65	20	42	19	63	3	25	12
Mean	97		66		51		29	

LSD (0.05) for comparing a hybrid mean between two soils is 25.8.
LSD (0.05) for comparing two hybrid means within a soil is 23.3.
LSD (0.05) for comparing two soil means is 13.5.

common hybrids of both years are presented in Table 7. Mean yields for several of the hybrids on the TLG treatment were similar to those obtained on the undisturbed Stoy soil. Hybrid yields from either of the mine soils were not comparable to those obtained on the Cisne soil. Hybrid LH123 x LH93 had the highest 2 year yields on the No TLG and Stoy soils, and ranked second on the TLG treatment.

The low yields from the mine soils in 1988 and 1989, especially on the No TLG scraper placed treatment, are assumed to be the result of increased sensitivity to weather stress. The increased sensitivity of these hybrids to stress may be due to the root-limiting characteristics of the compacted mine soils from scraper placement. Previous researchers have documented rooting differences for selected corn hybrids between mine soils (Fehrenbacher et al., 1982; Meyer, 1983). They concluded that confinement of the root systems in constructed mine soils was due to adverse soil physical parameters. Root cores have been taken from five selected hybrids on these plots and will be evaluated to determine rooting effectiveness in mine soils.

Table 5. 1988-89 mean yields across hybrids for mined and unmined soil treatments.

Soil treatment	1988	1989	Mean
		Yield, bu/a	
Cisne	97.7	108.4	103.0
Stoy	66.3	62.2	64.2
Scraper TLG	50.9	48.7	49.8
Scraper No TLG	29.4	17.8	23.6
LSD (0.05)	13.5	7.9	7.0

Table 6. Mean squares and level of significance for the various effects in the two year analysis of variance for 1988-1989 hybrid yield.

Source of variation	d f	Mean Square
Year (Y)	1	1056.38
Soil treatment (S)	3	148609.33**
Y x S	3	3102.61
Error (a)	12	1008.76
Hybrid (H)	16	857.95**
H x Y	16	673.79**
S x H	48	496.43**
H x Y x S	48	348.08
Error (b)	228	345.82

**, Significant at the 0.01 level of probability.

Table 4. Ranking of hybrids by yield for the 1989 Denmark Hybrid Study

Genotype	Cisne		Stoy		Scraper-TLG		Scraper-No TLG	
	bu/a	rank	bu/a	rank	bu/a	rank	bu/a	rank
Dennis 642	125	1	84	1	48	10	11	15
LH119 x LH51	121	2	42	20	35	17	9	16
Pioneer 3295	120	3	53	17	40	13	5	20
LH132 x LH123	118	4	61	12	46	11	17	10
Asgrow 2570	115	5	72	4	52	8	36	2
LH74 x LH123	113	6	61	10	65	3	22	6
FR27 x Mo17	110	7	70	5	63	4	15	12
LH119 x LH82	109	8	73	3	61	6	20	7
LH74 x LH51	109	9	57	14	66	2	22	5
Pioneer 3377	108	10	79	2	50	9	9	17
Pioneer 3320	108	11	55	16	34	18	8	18
Pioneer 3165	107	12	47	18	26	20	25	4
FR1141 x FR4326	106	13	70	6	44	13	14	13
LH136 x LH123	103	14	65	8	67	1	6	19
LH123 x LH93	103	15	64	9	63	5	43	1
FR27 x LH38	103	16	68	7	59	7	15	11
Zimmerman Z14W	101	17	45	19	40	14	27	3
Zimmerman Z28	97	18	57	15	46	12	20	8
LH82 x LH146	97	19	61	11	33	19	18	9
Dekalb 689	93	20	58	13	35	16	13	14
Mean	108		62		49		18	

LSD (0.05) for comparing a hybrid mean between two soils is 25.8
LSD (0.05) for comparing two hybrid means within a soil is 25.7
LSD (0.05) for comparing two soil means is 7.9.

Industry Mine

1989 Results

Hybrid plots at Industry Mine in west-central Illinois were planted on May 17 in 1989 under favorable moisture conditions. Emergence was good to excellent on both the cross-pit wheel spoil and undisturbed Keomah soil. Rainfall in May was near normal resulting in rapid early season growth. Precipitation in June and July was significantly below normal and stress symptoms were visibly apparent on both soils by early July. Hybrids on mine soil plots were exhibiting considerably more stress than hybrids on the Keomah soil plots. Limp leaves and tight rolls were common on most hybrids. However, one hybrid (LH123 x LH93), was quite conspicuous, in that no significant stress symptoms were visible compared to the other hybrids on mine soil. This difference in visible stress expression continued through most of the growing season. Rainfall in August was near normal but rainfall in September totaled only 0.94 inches, about 1/4 of normal. This increased sensitivity to weather stress of hybrids grown on the wheel spoil treatment may be due to root-limiting physical characteristics of the wheel spoil created by grading and topsoil replacement.

Results of the analysis of variance show that yield was significantly affected by both soil treatment and hybrids in 1989 (Table 8). No significant soil treatment by hybrid interaction occurred in the 1989 experiment. Yield results from this 1989 study are presented in Table 9. Yields on the Keomah soil were significantly higher than the wheel spoil for every hybrid. The hybrid LH123 x LH93, which was duplicated twice (two different seed lots), was the number 1 and 2 ranked hybrid on the mine soil. Yields of all hybrids grown on the wheel spoil are low due to weather induced stress. Hybrid yields on the Keomah soil were very good, given the weather conditions in 1989. Rainfall when pollination occurred, June 13 to July 17, totaled only 0.74 in.

Table 8. Mean squares and level of significance for the various effects in the analysis of variance for 1989 hybrid yield at Industry Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	1	156626.96**
Error (a)	6	1798.03
Hybrid (H)	24	781.89**
S x H	24	202.08
Error (b)	129	216.37

**, Significant at the 0.01 level of probability.

Table 7. Rankings of hybrids by mean yield for 1988-1989 Denmark Hybrid Study.

Genotype	Cisne		Stoy		Scraper TLG		Scraper No TLG	
	bu/a	rank	bu/a	rank	bu/a	rank	bu/a	rank
Asgrow 2570	115.4	1	70.8	3	50.8	8	35.8	2
Pioneer 3295	113.3	2	55.1	15	48.8	11	19.0	13
LH119 x LH51	112.4	3	52.6	16	40.2	16	14.7	14
Pioneer 3165	112.0	4	68.8	6	30.0	17	34.0	3
FR27 x Mo17	111.1	5	72.5	2	48.0	13	13.2	17
LH132 x LH123	109.2	6	62.9	12	50.7	9	33.4	4
LH123 x LH93	108.9	7	75.0	1	64.2	2	44.5	1
Pioneer 3320	108.6	8	64.9	10	41.3	15	14.2	16
Zimmerman Z28	102.6	9	65.6	9	49.2	10	29.1	5
LH74 x LH123	102.2	10	62.5	13	60.8	4	22.0	11
FR1141 x FR4326	102.0	11	68.9	5	44.5	14	14.2	15
Pioneer 3377	101.1	12	70.5	4	56.4	5	24.6	7
LH136 x LH123	99.6	13	66.4	8	64.1	3	23.4	9
FR27 x LH38	99.0	14	68.6	7	66.4	1	24.4	8
LH119 x LH82	98.0	15	64.5	11	53.3	7	26.8	6
LH74 x LH51	90.8	16	58.2	14	55.5	6	23.0	10
LH82 x LH146	80.8	17	51.6	17	48.1	12	21.3	12
Mean	103.0		64.2		49.8		23.6	

LSD (0.05) for comparing a hybrid mean between two soils is 25.5

LSD (0.05) for comparing two hybrid means within a soil is 25.2

LSD (0.05) for comparing two soil means is 7.0.

1990 Results

Plots were planted in 1990 on May 31. Soil moisture and seedbed conditions were very favorable to the planting operation. Emergence was excellent for all hybrids on both the mined and unmined land. Vigorous early season growth was enhanced by adequate precipitation events through June and July. Although June rainfall was 10 inches above normal rainfall was distributed into weekly events throughout the month. Little visible stress was evident at pollination in late July for any of the hybrids on either soil treatment. Below normal rainfall and above normal temperatures from mid-August to mid-September accelerated maturity and enhanced dry down of stalks and grain.

Results of the analysis of variance (Table 10) show that 1990 yield was not significantly affected by soil treatments but was significantly affected by hybrids. A significant soil treatment by hybrid interaction occurred in 1990 indicating hybrids responded differently to soil effects.

1990 yields of 23 individual hybrids on the wheel spoil treatment were not significantly different than yields on the undisturbed Keomah treatment (Table 11). The hybrid LH123 x LH93 yielded significantly higher

Table 10. Mean squares and level of significance for the various effects in the analysis of variance for 1990 hybrid yield at Industry Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	1	128.71
Error (a)	6	153.37
Hybrid (H)	24	1180.73**
S x H	24	368.95*
Error (b)	129	224.49

**, Significant at the 0.01 level of probability.
*, Significant at the 0.05 level of probability.

Table 9. Ranking of hybrids by yield for the 1989 Industry Hybrid Study.

Genotype	Wheel Spoil		Keomah	
	bu/a	rank	bu/a	rank
FR27 x Mo17	48.9	13	123.6	1
FR27 x LH38	52.0	12	115.8	6
FR1141 x FR4326	58.9	9	113.5	10
LH136 x LH123	60.1	7	114.8	9
LH119 x LH51	48.3	15	121.2	3
Zimmerman Z28	34.5	20	106.5	17
Asgrow 2570	33.0	22	121.5	2
LH132 x LH123	58.4	10	115.3	7
LH74 x LH123	61.4	4	100.4	21
LH82 x LH146	48.7	14	104.7	18
LH74 x LH51	43.1	18	107.1	16
LH119 x LH82	61.3	5	110.1	14
LH123 x LH93 (1)	68.6	1	116.7	5
Pioneer 3165	31.5	23	100.0	22
Pioneer 3320	33.4	21	101.6	20
Pioneer 3377	60.5	6	120.7	4
Pioneer 3295	61.5	3	111.6	13
Dennis 642	56.5	11	109.6	15
Dekalb 689	39.4	19	96.0	23
Zimmerman Z14W	27.4	25	75.4	25
LH136 x LH82	59.6	8	113.0	12
LH74 x LH82	44.4	17	114.9	8
LH136 x LH59	48.3	16	104.3	19
LH123 x LH93 (2)	64.5	2	113.0	11
Zimmerman Z54W	27.8	24	92.7	24
Mean	49.5		108.8	

LSD (0.05) for comparing a hybrid mean between two soils is 20.6 bu/a.
LSD (0.05) for comparing two hybrid means within a soil is 16.7 bu/a.
LSD (0.05) for comparing two means of a soil is 5.1 bu/a.

Table 11. Ranking of hybrids by yield for the 1990 Industry Hybrid Study.

Genotype	Wheel Spoil		Keomah	
	bu/a	rank	bu/a	rank
Pioneer 3241	162.5	1	165.9	1
LH123 x LH93	161.3	2	132.2	17
Agrigold XA216	153.4	3	135.9	14
Agrigold XA219	149.5	4	147.6	9
Pioneer 3377	147.6	5	142.1	12
LH119 x LH51	146.4	6	145.3	10
Agrigold E3009	144.8	7	158.5	3
Pioneer 3189	141.3	8	149.7	7
Agrigold A6615	140.0	9	139.6	13
Pioneer 3295	139.5	10	158.7	2
LH136 x LH123	138.8	11	151.1	6
FR27 x FRMo17	138.3	12	154.5	4
FR1141 x FR43	137.4	13	131.7	18
Agrigold E4012	136.0	14	128.7	21
Asgrow 2570	135.6	15	144.2	11
LH74 x LH123	134.6	16	133.6	15
LH136 x LH82	133.7	17	130.9	19
LH74 x LH51	130.1	18	133.1	16
LH132 x LH123	129.2	19	148.0	8
LH119 x LH82	128.2	20	112.0	24
LH136 x LH59	126.4	21	130.6	20
FR27 x LH38	122.9	22	116.8	23
FR618 x FR600	121.9	23	153.8	5
LH74 x LH82	117.7	24	128.4	22
LH146 x LH82	115.7	25	99.6	25
Mean	137.3		138.9	

LSD (0.05) for comparing a hybrid mean between two soils is 20.7 bu/a.
LSD (0.05) for comparing two hybrid means within a soil is 20.9 bu/a.
LSD (0.05) for comparing two means of a soil is 4.3 bu/a.

on the wheel spoil treatment. The FR618 x FR600 hybrid yielded significantly higher on the Keomah soil. Mean yields of the wheel spoil treatment and the Keomah soil were not significantly different when averaged over all 25 hybrids.

1991 Results

Plots were planted on May 2 under excellent soil conditions. Emergence was good to excellent for hybrids on both soil treatments. Four inches of intense rainfall occurred 10 days after planting affecting stands on some mine soil plots. Yield sampling was not compromised however, as stand damage was avoided during harvest. Normal June rainfall allowed for vigorous early season growth . July was characterized by below normal precipitation and above normal temperatures. Mid to late July was extremely hot creating considerable stress on all hybrids during the pollination period. Ear development and grain fill was enhanced by cooler temperatures and adequate rainfall in August.

Analysis of variance of 1991 data show that yield was affected by both soil treatment and hybrids (Table 12). No significant soil treatment by hybrid interaction was observed in 1991. Yields of 11 hybrids grown on the wheel spoil were not significantly different than yields of the same hybrid grown on the undisturbed Keomah soil (Table 13). Mean yield of the 20 hybrids on Keomah soil was significantly higher (0.05 level) than mean yield of the 20 hybrids on the wheel spoil in 1991. Weather induced stress affected hybrids on the wheel spoil more than hybrids on the undisturbed Keomah.

1989-91 Mean Yields

Years, soil treatments, and hybrids significantly affected corn yields across the three year period of this study (Table 14). Year to year variation in hybrid yield is attributed to weather induced stress. Weather in 1990 was more favorable for corn production than 1989 or 1991. Significant soil by year (0.01 level) interaction indicate soil treatments responded differently to year effects (environment). Yield variation of the wheel spoil was more closely associated to weather variation than was the undisturbed treatment.

Three year mean yields for this study show the yields of the genotypes to be superior on the undisturbed Keomah soil (Table 15). Within years, mean hybrid

Table 12. Mean squares and level of significance for the various effects in the analysis of variance for 1991 hybrid yield at Industry Mine.

Source of variation	d f	Mean Square
Soil treatment (S)	1	12110.28**
Error (a)	6	891.36
Hybrid (H)	24	836.18*
S x H	24	375.16
Error (b)	129	440.85

**, Significant at the 0.01 level of probability.

*, Significant at the 0.05 level of probability.

Table 13. Ranking of hybrids by yield for the 1991 Industry Hybrid Study.

Genotype	Wheel Spoil		Keomah	
	bu/a	rank	bu/a	rank
Pioneer 3140	135.9	1	147.8	2
LH123 x LH93	129.6	2	132.6	8
Asgrow 2570	127.3	3	136.3	5
Pioneer 3165	121.8	4	150.4	1
FR27 x Mo17	121.1	5	115.7	18
Dekalb 689	117.5	6	110.7	20
Pioneer 3189	116.7	7	118.9	15
LH119 x LH51	115.4	8	130.8	9
Pioneer 3377	114.8	9	124.0	13
Dekalb 649	113.2	10	134.3	6
Dennis 642	111.5	11	130.8	10
Pioneer 3379	110.5	12	138.7	4
LH74 x LH123	108.9	13	117.6	16
Pioneer 3241	106.0	14	133.7	7
LH132 x LH123	103.0	15	116.6	17
FR1141 x FR4326	102.6	16	123.6	14
Pioneer 3180	100.3	17	140.2	3
FR618 x FR4326	97.0	18	125.0	12
FR618 x FR600	90.8	19	128.3	11
FR27 x LH38	79.3	20	115.6	19
Mean	111.2		128.6	

LSD (0.05) for comparing a hybrid mean between two soils is 24.9bu/a.

LSD (0.05) for comparing two hybrid means within a soil is 22.8 bu/a.

LSD (0.05) for comparing two means of a soil is 11.5 bu/a.

Table 14. Mean squares and level of significance for the various effects in the two year analysis of variance for 1989-1991 hybrid yield at Industry Mine.

Source of variation	d f	Mean Square
Year (Y)	1	48637.08**
Soil treatment (S)	1	31289.71**
Y x S	1	18138.57**
Error (a)	12	452.30
Hybrid (H)	16	1043.57**
H x Y	16	321.68
S x H	16	404.38
H x Y x S	16	291.51
Error (b)	181	389.41

**, Significant at the 0.01 level of probability.

yield on the Keomah soil was significantly higher than the wheel spoil in 1989 and 1991, years of greater weather stress. No yield difference among these soil treatments occurred in 1990.

Three year mean yields for the 9 common hybrids of both years are presented in Table 16. Four hybrids (LH123 x LH93; Pioneer 3377; LH74 x LH123; FR1141 x FR4326) produced three year mean yields on the wheel spoil comparable to three year mean yields on the Keomah soil.

SUMMARY AND CONCLUSIONS

Data from hybrids grown at Denmark Mine and Industry Mine support the following general conclusions: (i) The potential to minimize the effects of stress on corn grown on mine soils exists through hybrid selection of adapted genotypes. Of the 12 common hybrids between the southern and western Illinois locations, three hybrids (LH123 x LH93; LH136 x LH123; LH74 x LH123) on the mine soils were ranked in the top five hybrids over the two year period for both locations. Hybrids with the highest yield potential on undisturbed soils did not necessarily produce the highest yields on disturbed soil plots. (ii) Weather variables were associated more with yield variation on the mine soils than the undisturbed soil treatments. (iii) Over a two year period, the Cisne soil in southern Illinois, and over a three year period the Keomah soil in western Illinois were superior to the mine soils for growing corn when averaged over all hybrids. iv) The scraper placed mine soil of southern Illinois yielded substantially lower than the wheel spoil soil of western Illinois. This is due to differences in the quality of soil materials and levels of soil compaction between sites.

Table 15. 1989-91 mean yields across hybrids for mined and unmined soil treatments.

Soil treatment	1989	1990	1991	Mean
		Yield, bu/a		
Wheel Spoil	49.5	137.7	111.2	99.5
Keomah	108.8	138.9	128.5	125.4
LSD (0.05)	5.1	4.3	11.5	6.2

Table 16. Ranking of hybrids by yield for the 1989-91 Industry Hybrid Study.

Genotype	Wheel Spoil		Keomah	
	bu/a	rank	bu/a	rank
LH123 x LH93	119.8	1	127.2	5
Pioneer 3377	107.7	2	128.9	4
Asgrow 2570	104.6	3	135.1	1
LH119 x LH51	103.4	4	133.5	2
FR1141 x FR4326	103.2	5	122.9	7
FR27 x Mo17	102.8	6	132.0	3
LH74 x LH123	101.6	7	118.7	8
LH132 x LH123	96.9	8	126.6	6
FR27 x LH38	84.7	9	116.0	9
Mean	102.7		126.6	

LSD (0.05) for comparing a hybrid mean between two soils is 21.8 bu/a.

LSD (0.05) for comparing two hybrid means within a soil is 21.3 bu/a.

LSD (0.05) for comparing two means of a soil is 4.4 bu/a.

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