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.

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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

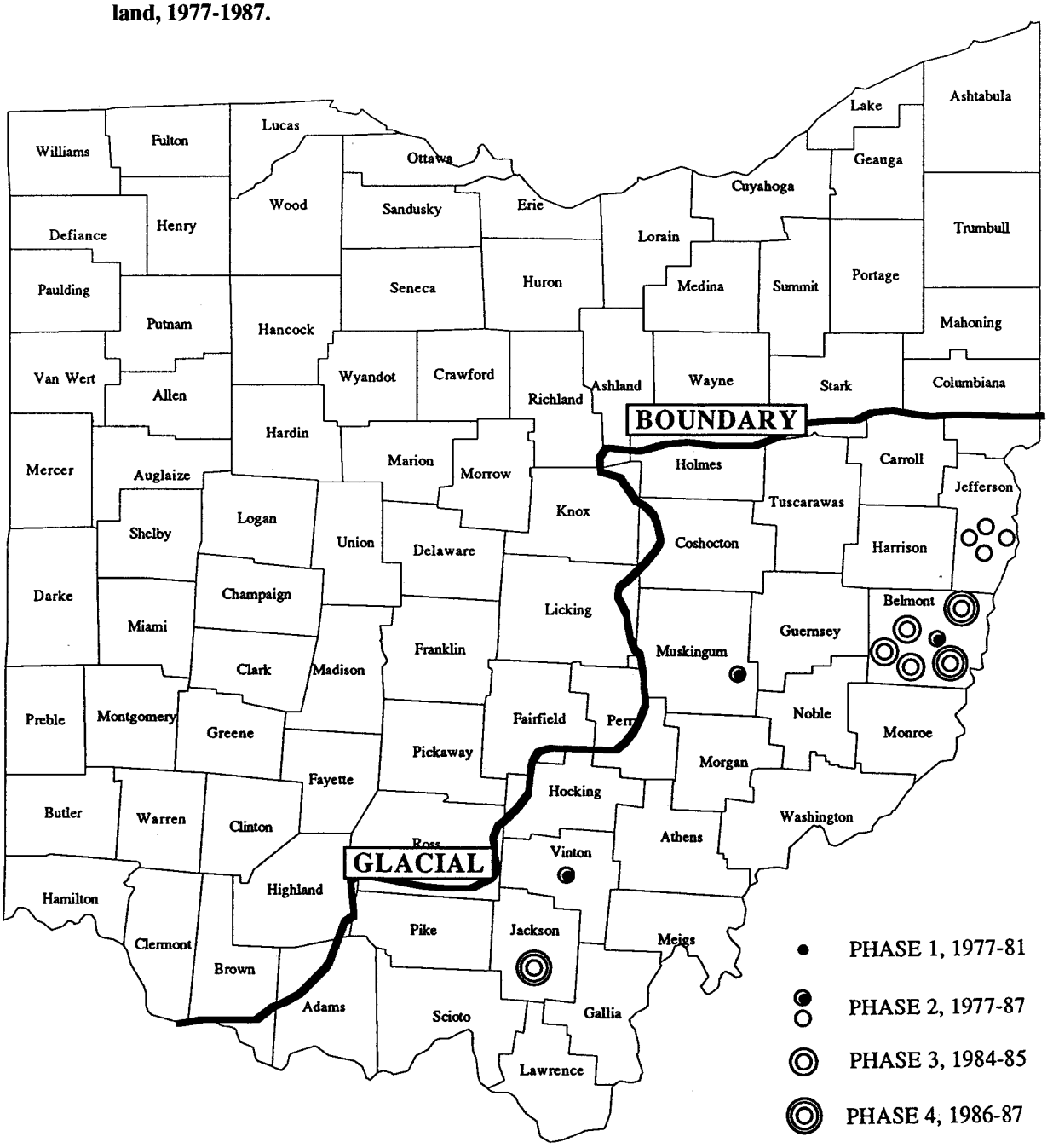
[1]Farmerstown soils on these plots have a higher reaction in the substratum (2C horizon) than is defined as the range for the series. This difference, however, does not significantly affect the use or management of the soils.
[2]Skeletal: rock fragments 2mm in diameter or larger, >35% by volume.

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	Horizons & Depth	Year	Yield
	(inches)			(bu/A)
Belmont Co.	36	AP - 6	1979	138**
(Pickenpaugh)*		B/A - 10	1980	108
		B/C - 20	1981	143
Jefferson Co.	32	AP - 5	1982	104
(Rector A)		C1 - 24	1983	41
		C2 - 3+	1984	83
Jefferson Co.	23	AP - 5	1982	109
(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 (inches)	Farmerstown-Belmont Co. (gm/sample)	Fairpoint-Jackson Co. (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.

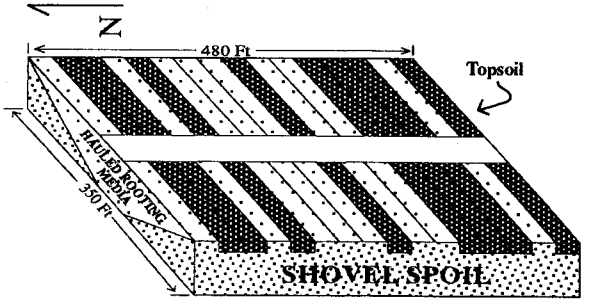
The objective of this research is to characterize and evaluate the effects of selected reclamation methods on soil productivity.

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.

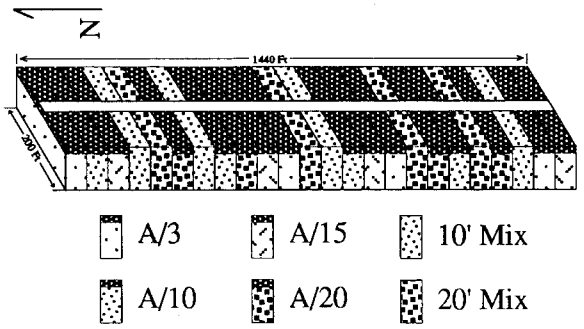
The mix plots, constructed in 1980, consist of a randomized complete block design with four replications (Figure 2) with the following treatments:

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 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.

Figure 2. Captain Mix Plots.



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 over-

burden , 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.

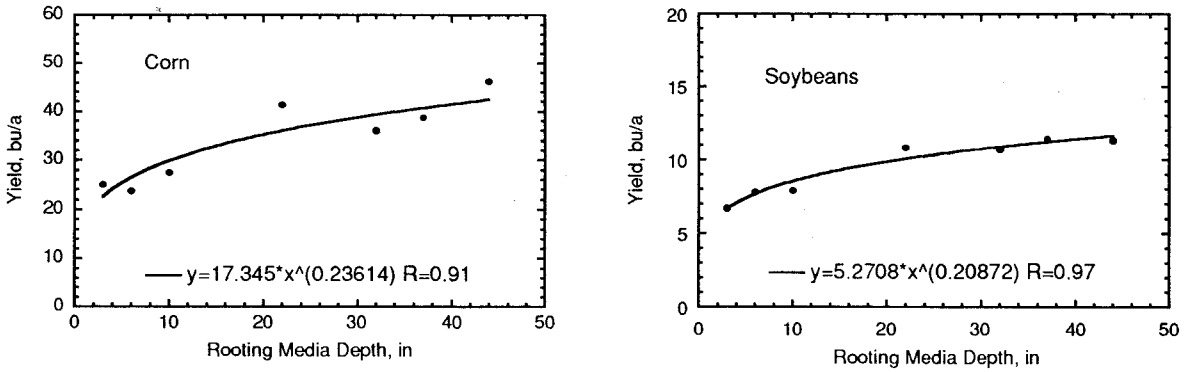
Depth	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
	Yield, bu/a											
Topsoil/Root Media:												
3"	19	0	9	16	0	0	14	2/		0	0	0
6"	22	0	11	18	0	0	12			0	0	0
10"	23	0	12	16	0	0	12			0	0	0
13"		0	14	18	0	0						
19"	31						15					
22"	30	0	15	22	0	0	20			0		
30"		0	13	24	0	0						
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 HCL1/	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.

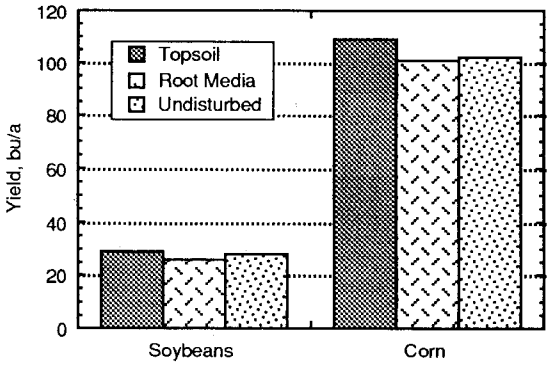
[4] Soybeans were not grown in 1986 and 1987.

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

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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.

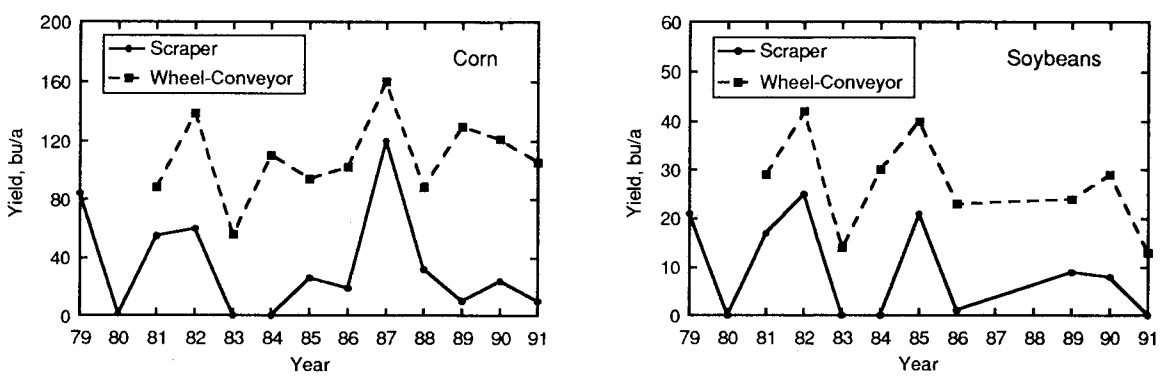

Table 6. 1991 soil test means for soil treatments (A horizon overlying B horizon) for Captain Mix and Captain Wedge.

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:

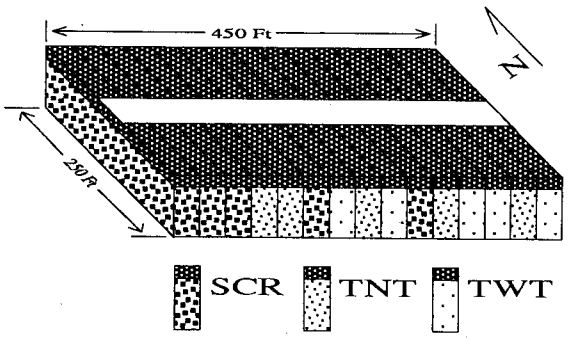
SCR Topsoil replaced over scraper-hauled rooting media.

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.

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

	Depth			
Treatment	9-18"	18-27"	27-36"	36-44"
	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.

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.

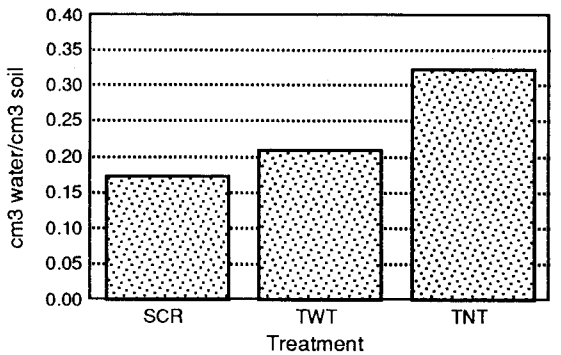


Table 3. 1985-91 mean values for measured corn yield variables.

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

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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.

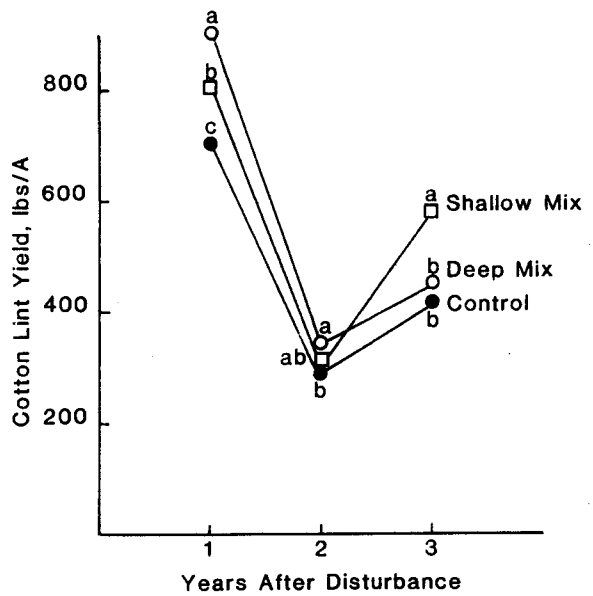

Table 2. Characteristics of soils and mixed overburden materials from the Brazos and Trinity River research site. Samples were from the top 6 inches of the original soil or the replaced overburden mix.

Parameter	Alluvial Valley				
	Brazos			Trinity	
Soil Series	Roetex	Shallow† mix	Deep‡ mix	Kaufman	Deep§ 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}		
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.

	Time	
Variable	0	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 $4m^2$ sample (combining four $1m^2$ 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		1986	1987	1988	1989	1990	1991	Mean
					Year of Data			
					(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.

		Year of Data[1]				
Location		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.

		Year of Data[1]				
Position/Mean		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.

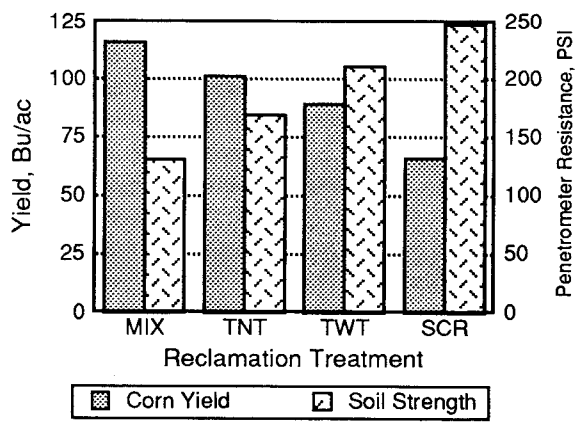
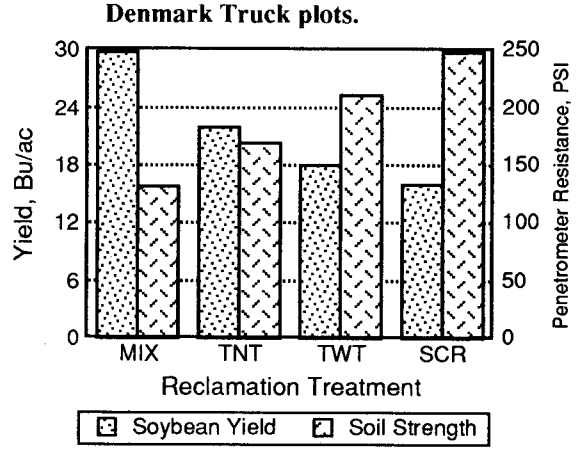


Figure 2. 1985-90 mean soybean yields and soil strength (9-44 in Avg) of Captain Mix and Denmark Truck plots.



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.

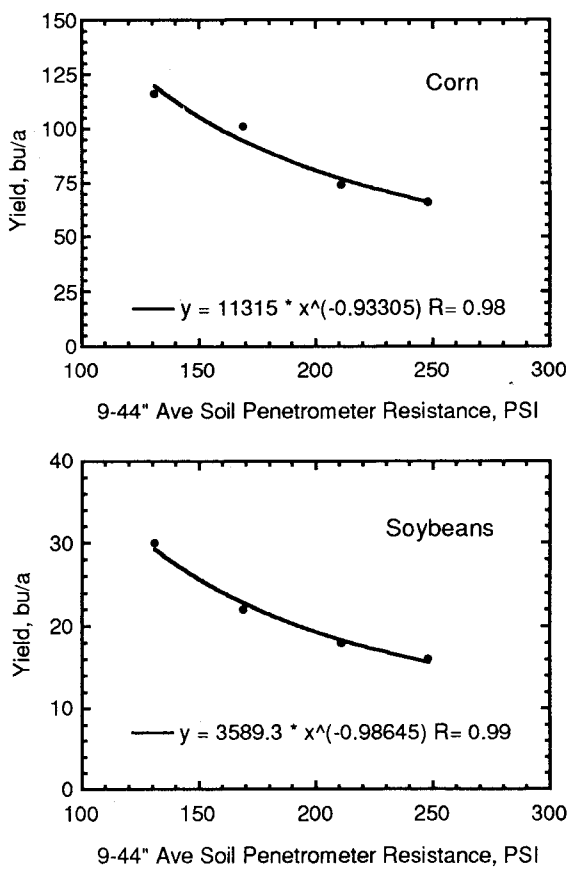
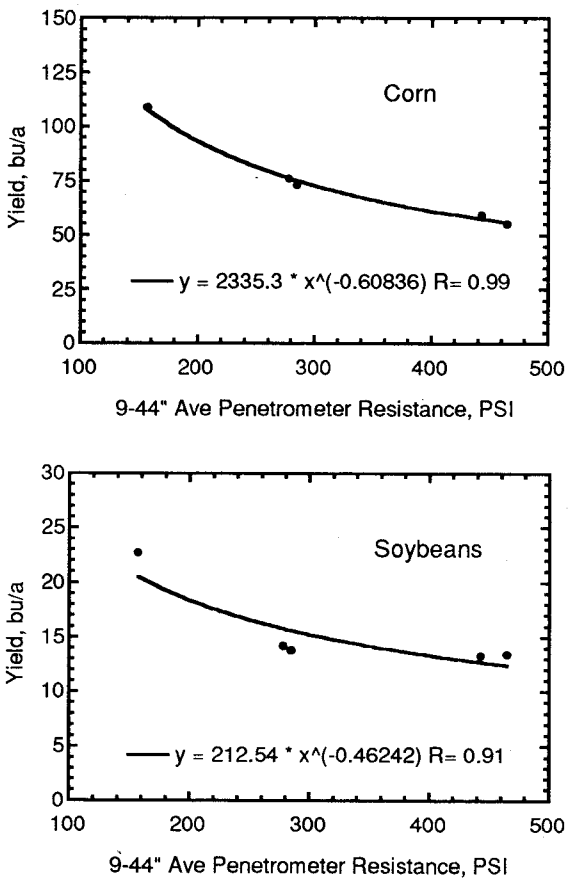


Figure 4. Relationship of penetrometer resistance and 1988-90 crop yields at Burning Star #2.



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).

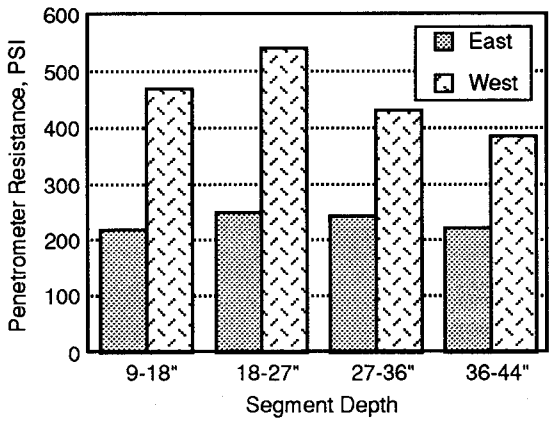


Figure 6. Comparison of tillage treatments on 9-44 in ave soil strength of west blocks(1-3) and east blocks(4-6).

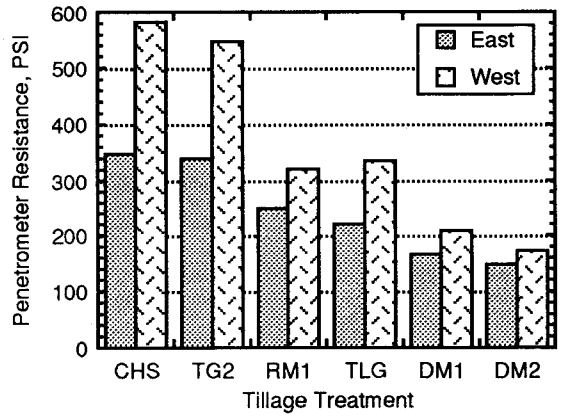


Table 3. Corn yields comparing blocks 1-3 (west side) to blocks 4-6 (east side).

	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.

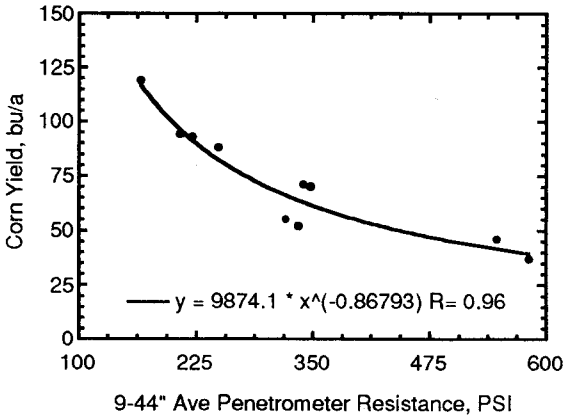


Figure 8. Regression of Blocks 1-3 and Blocks 4-6 mean soil strength with 1988-1989 mean soybean yields of blocks 1-3 and blocks 4-6.

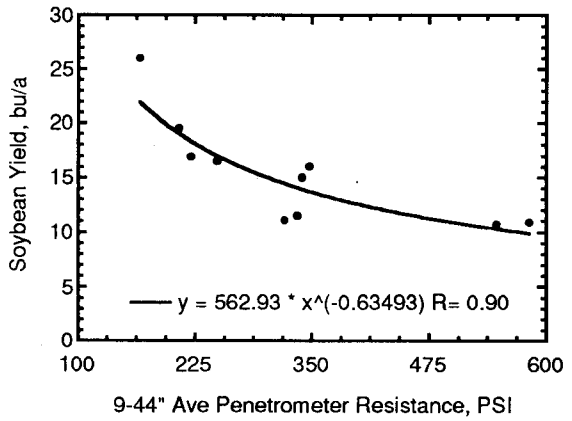


Table 5. Soil test results of rooting media (24 in depth) comparing blocks 1-3 (west side) to blocks 4-6 (east side).

		Particle Size			
TRT	Side/Blocks	% Sand	% 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.

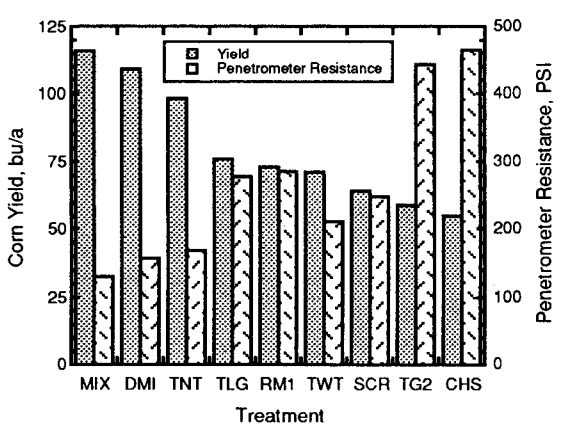
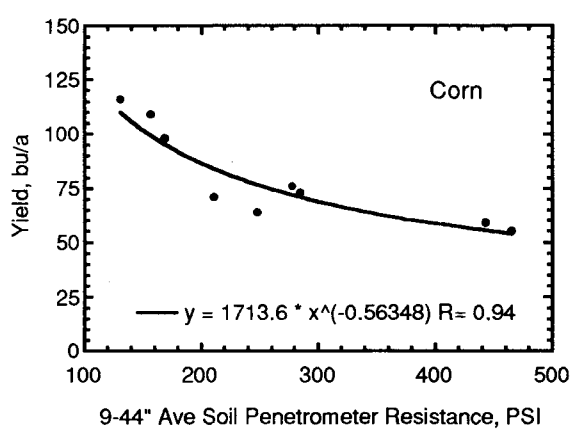


Figure 10. Regression of 1988-90 mean corn yields to 9-44" average soil strength of Captain Mix, Denmark Truck and Burning Star #2 treatments.



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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 soy-

beans. 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.

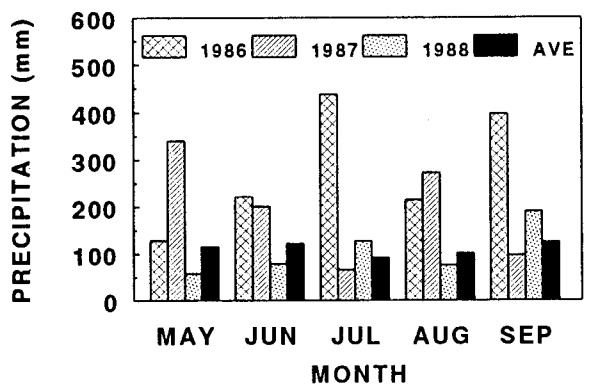

Table 2. Effects of subsoil replacement on rowcrop yields of reconstructed surface-mined soils in S.E. Kansas.

Year	Subsoil depth	Yield[a,b] GS-GS	SB-GS	Soybean
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.

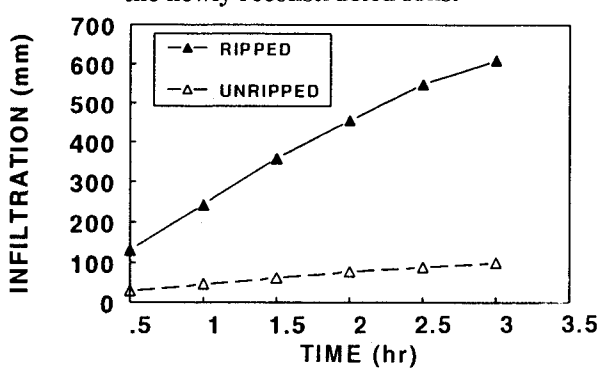

Table 3. Effects of ripping newly reconstructed surface mined soils on rowcrop yields in S.E. Kansas.

		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

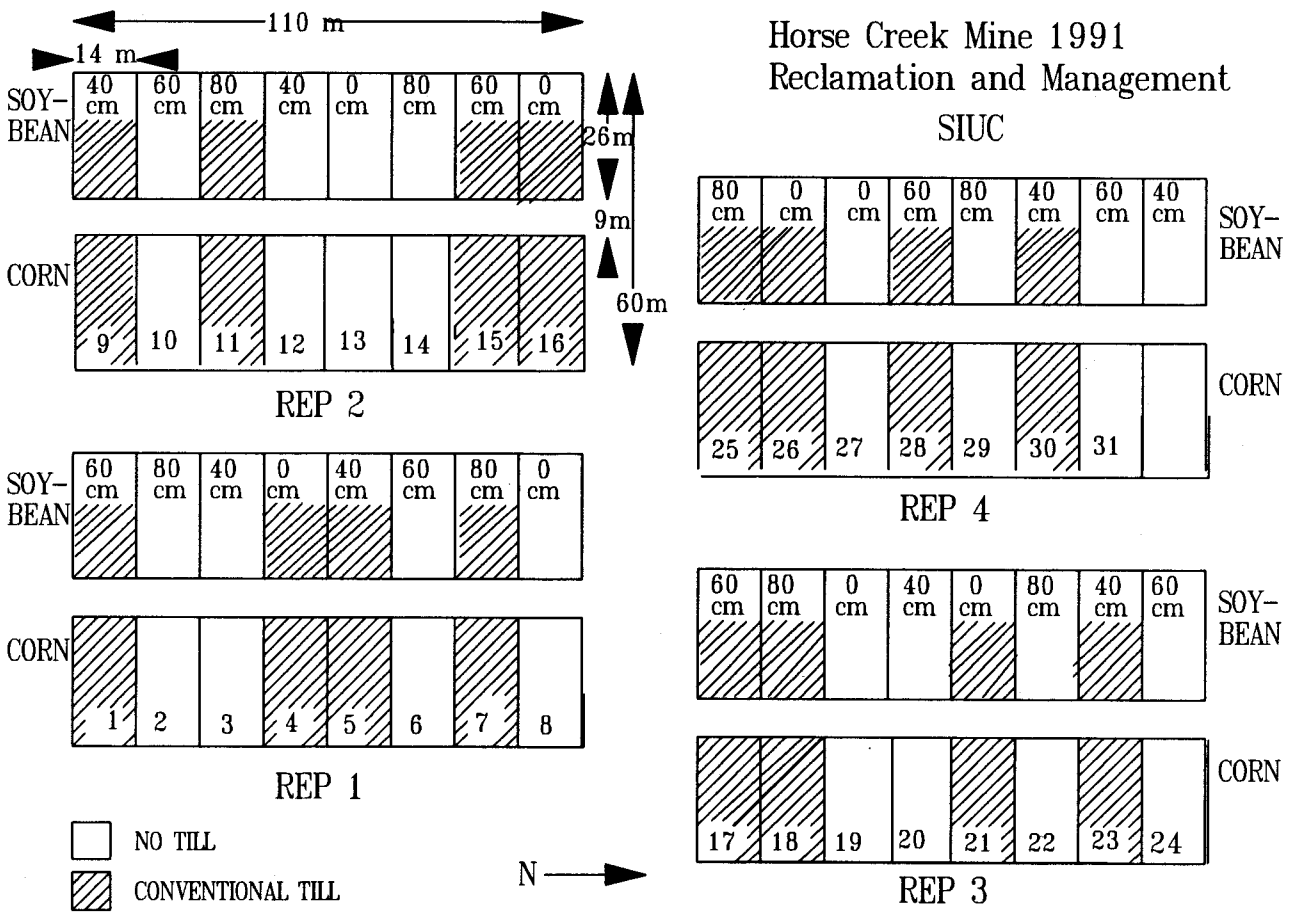
The experimental site is located at the Arch of Illinois Inc., Horse Creek Mine near Conant, in Perry County, Illinois. Prior to mining, the soils at the study area were classified as a Stoy and Weir silt loam series and the Hoyleton-Darmstadt and Cisne - Huey silt loam associations (Grantham and Indorante, 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_2O_5, and 400 kg ha^{-1} (360 lb/ac) of K_2O. 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/cm³ which increased to 1.82 g/cm³ 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.

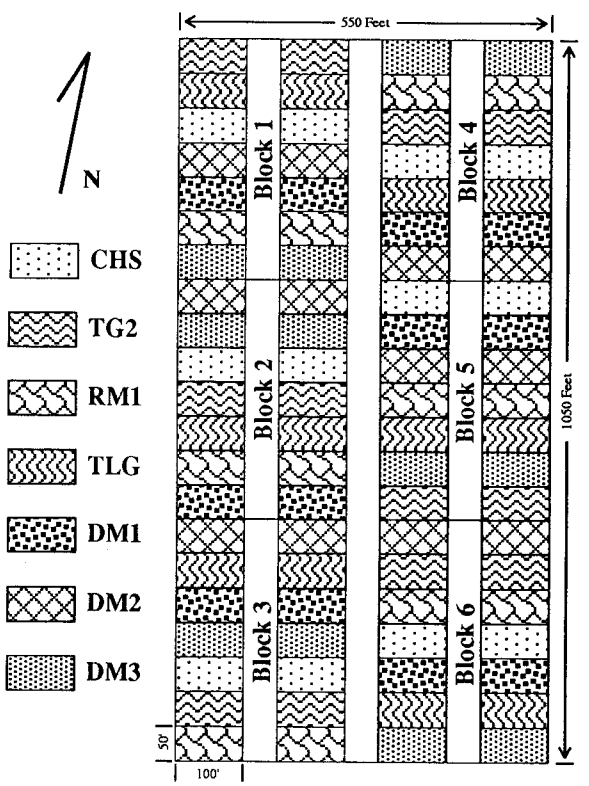
Experimental Design and Layout

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	Soil Depth Seg 2 9-18"	Seg 3 18-27"	Seg 4 27-36"	Seg 5 36-44"
	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

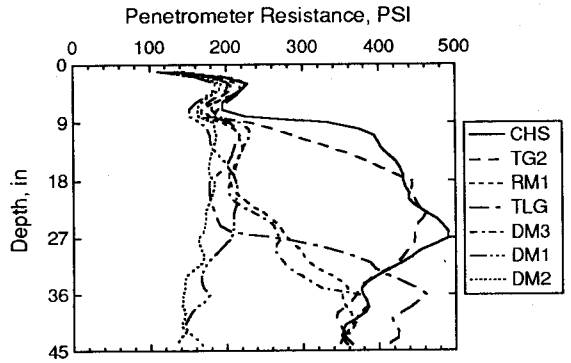


Table 4. Penetrometer data from BS#2 plots after tillage.

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).

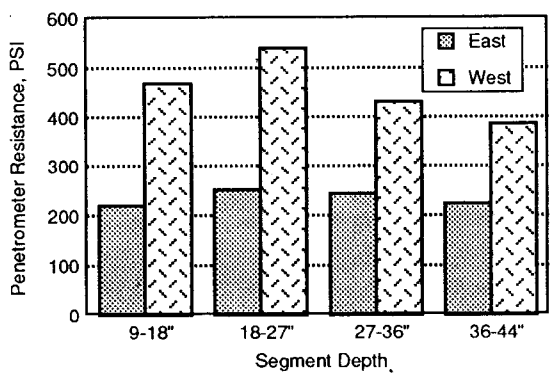


Figure 4. Comparison of tillage treatments on 9-44" ave soil strength of west blocks(1-3) and east blocks(4-6).

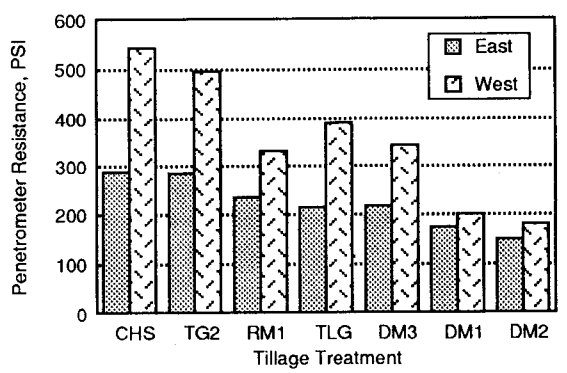


Table 7. 1988-91 mean values for measured agronomic variables for corn.

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).

	Tillage Treatment							
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).

	Tillage Treatment							
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.

TRT	Depth, ft 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.

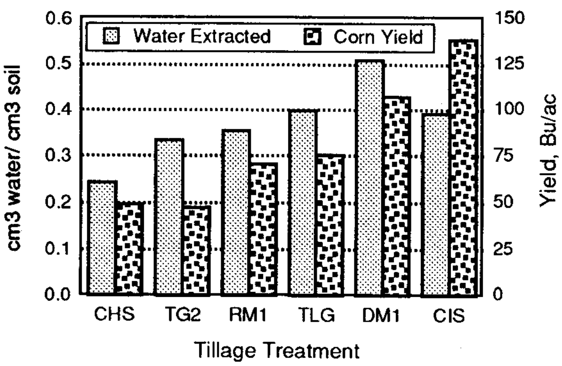


Table 12. 1988-89 Burning Star #2 net water extraction June to August.

TRT	Depth, ft 1	2	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.

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