Physical Properties of Deep Tilled Surface Mined Soils

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

INTRODUCTION

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

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

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

MATERIALS AND METHODS

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

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

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

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

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

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

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

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

A deep-profile penetrometer (Hooks and Jansen, 1986) was used to measure soil strength after tillage and during crop growing season. Because soil water content has a strong influence on soil strength, in-season measurements were expressed as a fraction of the untilled check. Correcting for concurrent soil strength in the untilled check normalizes the data and allows comparison across years.

Table 1. Tillage equipment description.

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

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

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

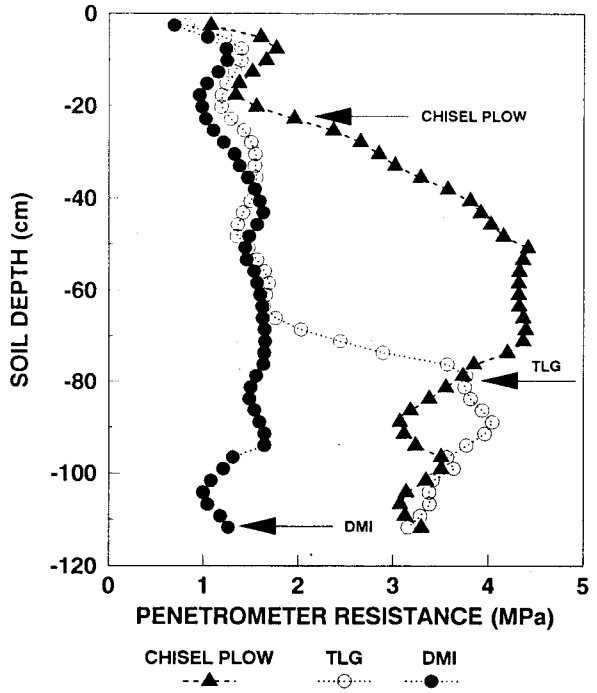
RESULTS AND DISCUSSION

Effects of deep tillage on soil strength

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

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

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



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

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

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

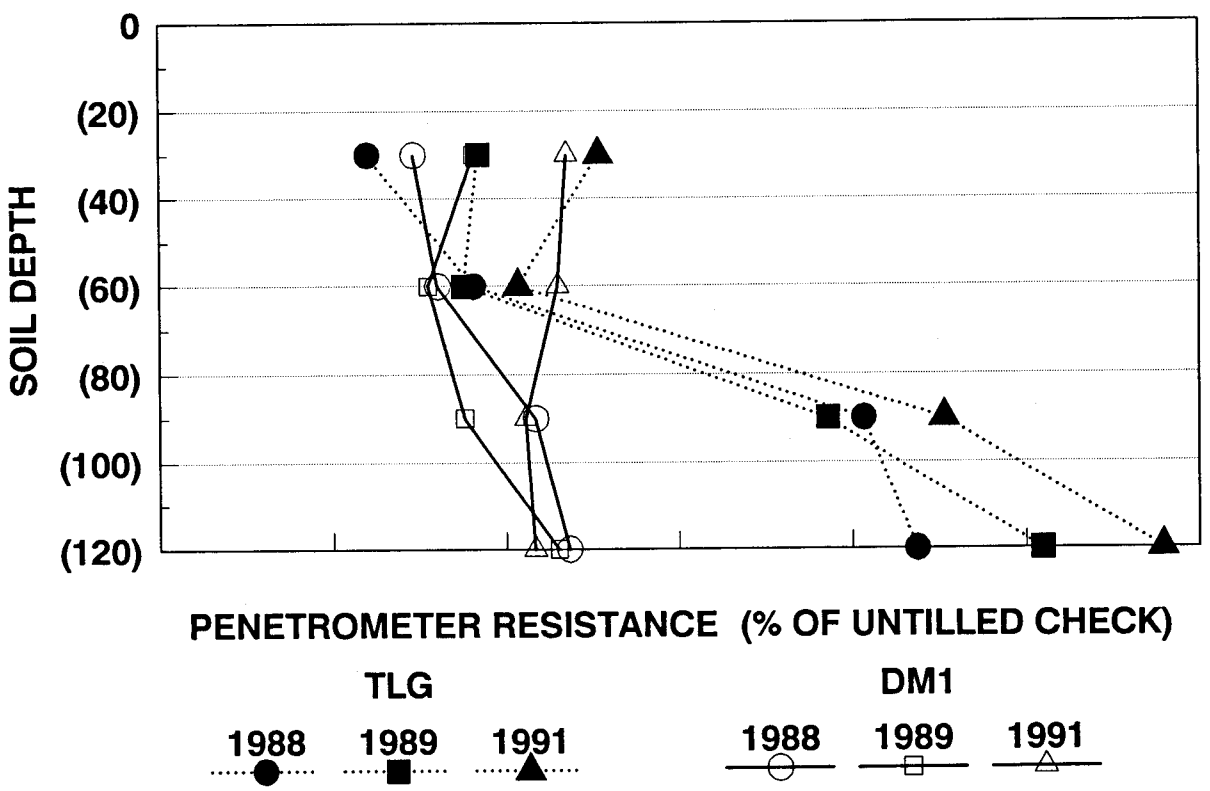
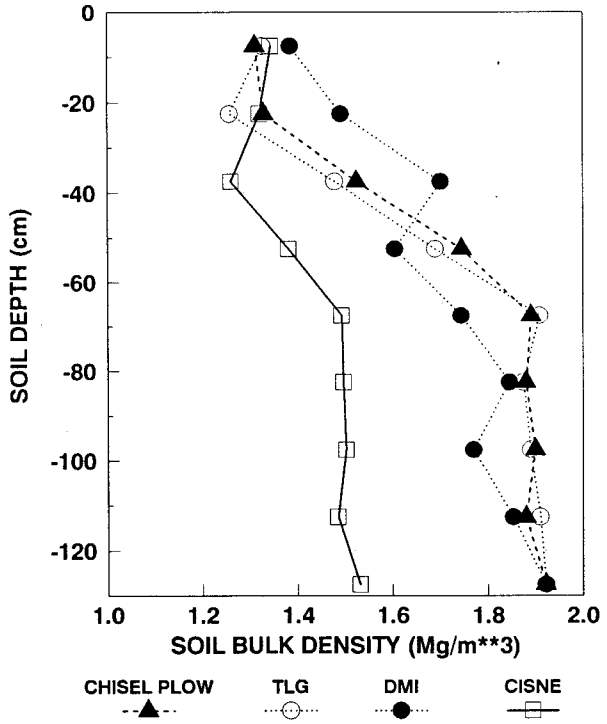


Figure 3. Bulk density profiles of chisel plow, TLG, and DMI tilled mine soils compared with an unmined Cisne silt loam (control) taken four years after tillage application.



sampling technique because it includes the entire soil volume.

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

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

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

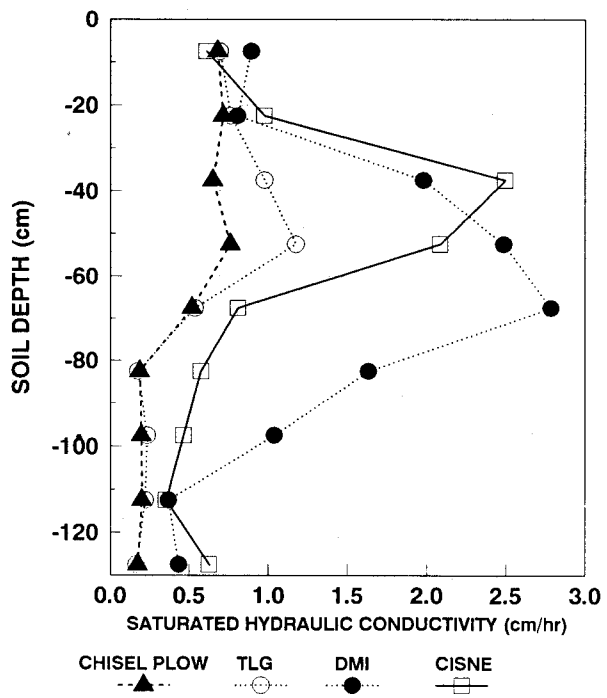


Figure 5. Porosity profiles (0-440 cm tension) for chisel plow, TLG, and DM1 soils compared with an unmined Cisne silt loam (control) taken four years after tillage application.

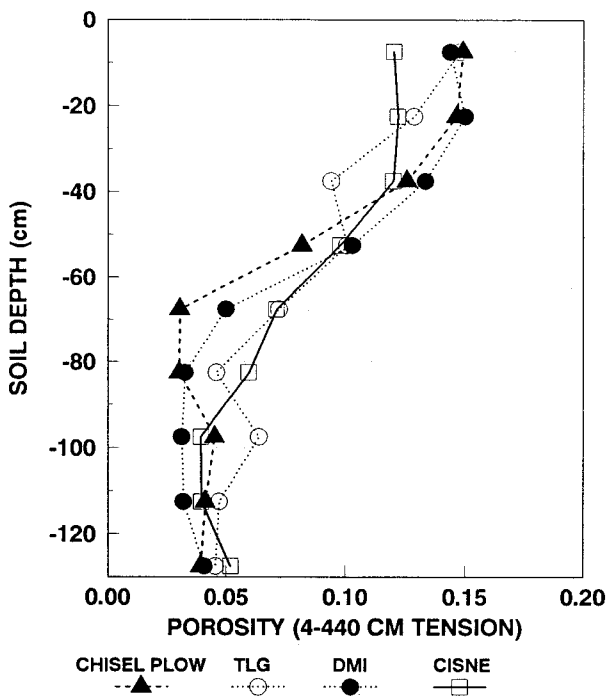


Figure 6. Soil water characteristics for 5 soil depths in chisel plow, TLG, and DM1 treated soils taken four years after tillage application.

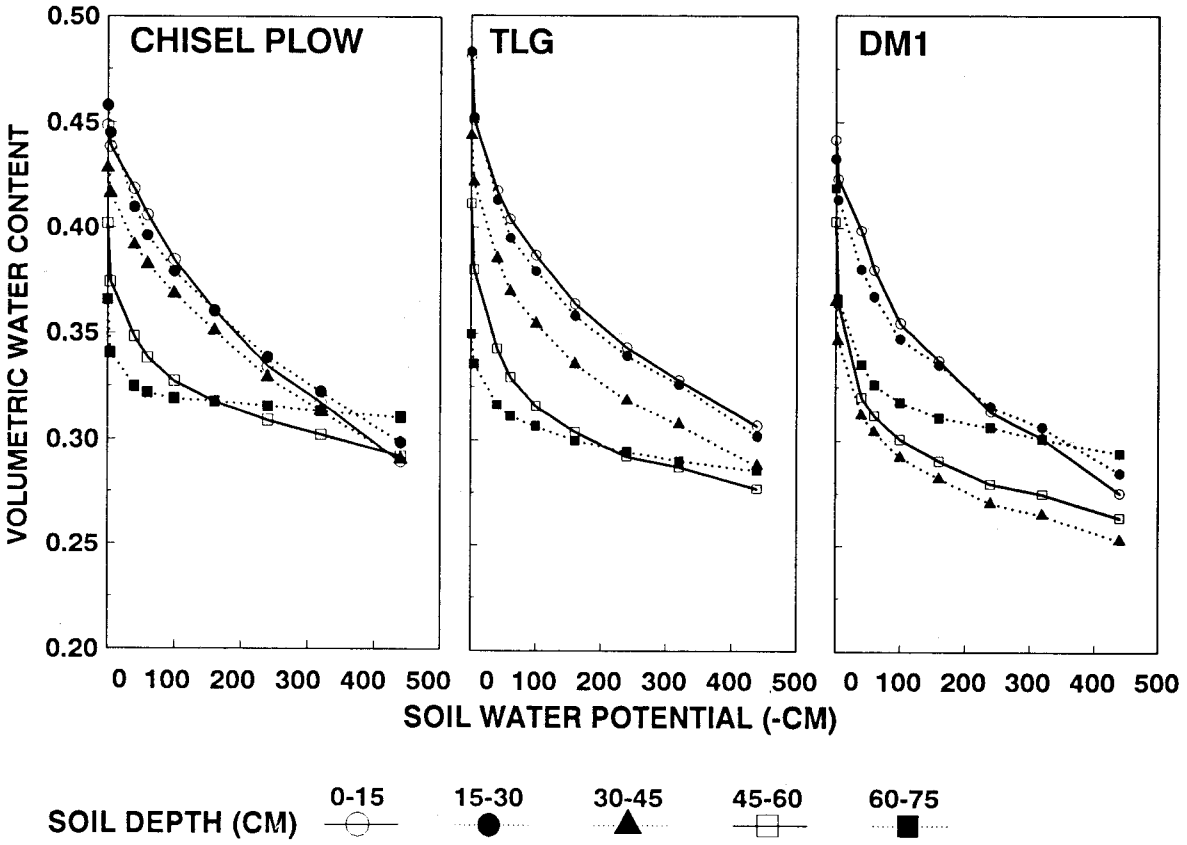


Table 2. Tillage effects on corn and soybean grain yields for 1988-1991 in harvest area adjacent to soil property study.

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

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

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

[3/] No sample

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

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

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Computer Tracking of Revegetation Operations using RODA

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

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

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

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

DESCRIPTION

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

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

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

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

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

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

RODA STRUCTURE

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

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

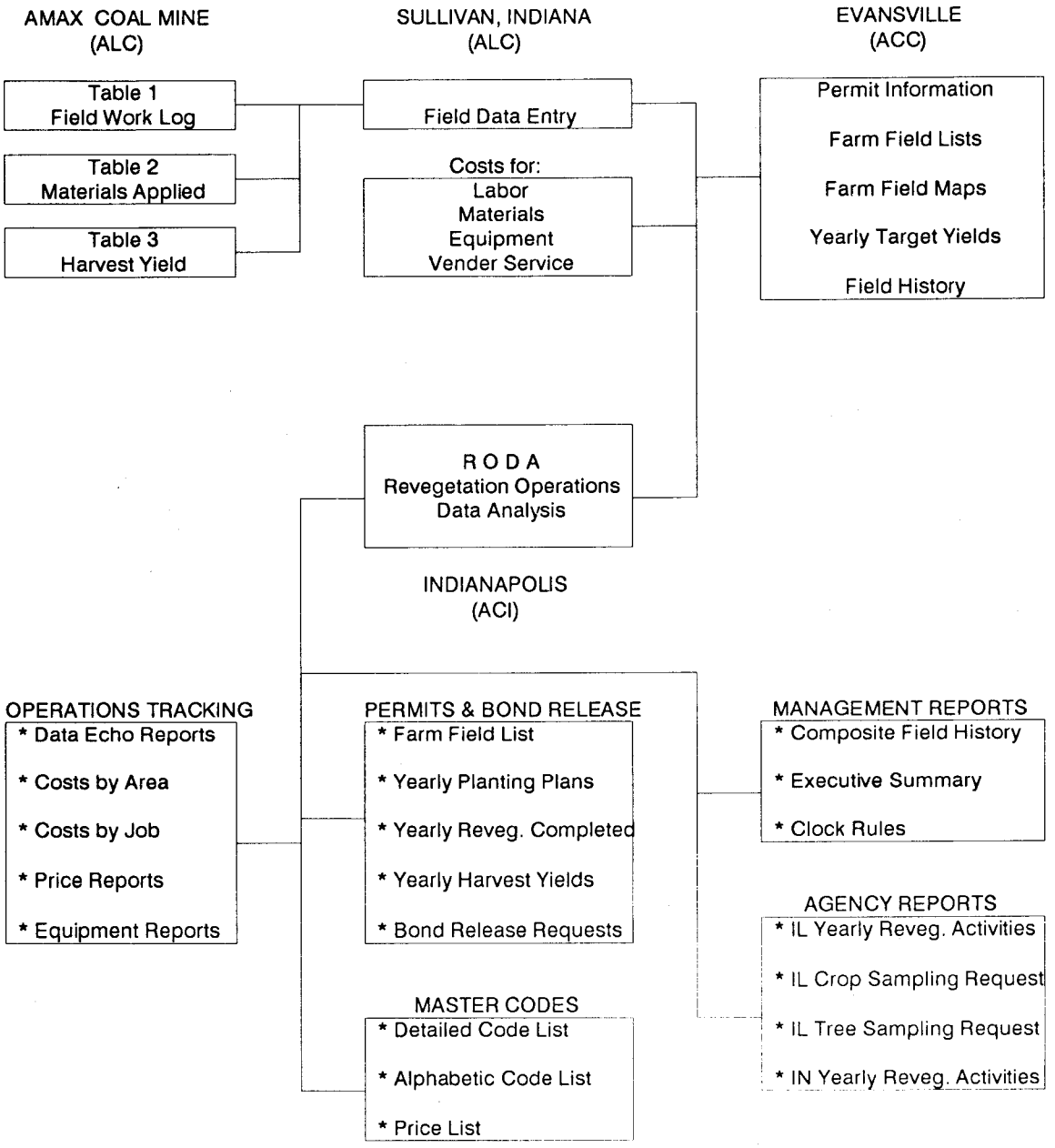
These modules are selected from RODA's main menu. Options available in each module will be discussed in more detail.

Revegetation Operations Tracking and Costing

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

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

Figure 1. RODA information flow chart.



* = RODA Report
ALC = Ayrshire Land Company, Inc.
ACC = AMAX Coal Company, Inc.
ACI = AMAX Coal Industries, Inc.

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

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

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

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

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

POWER UNIT

NAME _____

ASSET ID NO. _____

MINE _____

WEEK ENDING _____ (mm/dd/yy)

TABLE 1 Page ___ of ___

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

Table 2. Materials applied log.

MINE _____

WEEK ENDING _____ (mm/dd/yy)

TABLE 2 Page ___ of ___

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

Table 3. Harvest yield data log.

MINE _____

WEEK ENDING _____ (mm/dd/yy)

TABLE 3 Page ___ of ___

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

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

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

Echo reports
- Equipment and labor field log
- Materials applied log
- Harvest yield log

Costing reports
- Activity costs by area
- Activity costs by job

Price reports
- Labor prices
- Master code prices

Other reports
- Vendor list
- Equipment list
- Equipment depreciation
- Equipment cost & usage
- Month closing status

PERMITS, FIELDS, AND BOND RELEASE

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

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

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

Farm Field List

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

Yearly Plans

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

Yearly Planting Summary

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

Yearly Yields/Standards Checks

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

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

Pre-RODA Reclamation History

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

Pre-RODA Field Numbers

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

RODA Reclamation Clock Rules

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

Permit List

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

Yearly Target Yields

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

RODA REPORTS ON PERMITS, FIELDS, AND BOND RELEASE

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

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

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

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

MASTER CODE INFORMATION

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

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

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

Field work codes
- Areas
- Jobs
- Methods

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

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

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

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

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

AREA ID	
#	Field Number
AA	Ancillary Area
BA	Basin
HR	Haul Road
MA	Miscl. Area
JOB DONE TO EQUIP	
PM	Preven. Maint.
R	Repairs
JOB DONE TO AN AREA	
AF	Apply Fertilizer
AFC	Apply Fert-Corn
ALIM	Apply Lime
AP	Apply Pesticides
APC	Apply Pest-Corn
CM	Crimp Mulch
DR	Debris Removal
EC	Erosion Control
ECBB	EC-Bale Buster
ECFM	EC-Finn Type
H	Harvest
HCO	Harvest-Corn
LL	Land Level
LT	Load/Transport
LTCO	LT Corn
MJ	Miscellaneous Job
MOW	Mow
PLT	Plant
PLTC	Plant-Corn
RA	Raking
T	Tillage
TCUL	T Cultimulcher
TD	T Deeper than 24"
TDSK	T Disk
VT	Vendor tillage
VTD	VT Deeper than 24"
FLUID TYPE & UNITS	
ANFZ	Antifreeze (qts)
D	Diesel (gal)
G	Gasoline (gal)
HY	Hydraulic Fluid (qts)
OIL	Oil (qts)
TR	Trans. Fluid (qts)

FIELD WORK: METHODS	
AB	Aerial broadcast
BR	Baling round
DP	Drill or planter
GB	Ground broadcast
HP	Hand plant
MP	Machine plant
MATERIALS: MULCHES	
HMUL	Hydromulch fiber
HRBN	Hay, round bale, No.
SSBT	Straw, sq. bale, ton
WC	Wood chips
MATERIALS: TACKINGS	
CHV	Curlex-high velocity
ENET	Erosion netting
ENKA	Enkamat 7010
NAPM	N.A. P300 polymat
MATERIALS: PESTICIDES	
ATZ	Atrazine
BRON	Bronco
FUR	Furdan
KER	Kerb
LASO	Lasso
LORS	Lorsban
RUP	Roundup
FERTILIZER/LIME	
F0060	Muriate of potash
F0440	Tri. super phosphate
F1846	Ammonium phosphate
FB1	Fertilizer-borate 40
FZN1	Fertilizer-zinc sulfate
F1212	Fert. blend 12-12-12
L1	Lime-calcite
VENDOR APPLICATION CHARGES	
VA1	Ground broadcast
VA8	Machine plant trees
VA13	Vendor tillage
VA19	Vendor cultimulcher
VA20	Replant trees by hand
VA22	Ground spray

VENDOR HARVEST CHARGES	
VH1	Combine wheat
VH2	Combine corn
VH5	Baling, square
VH8	Transport bales, round
VH9	Transport grain
TREES/SHRUBS	
APL	American plum
BC	Black cherry
CHO	Chestnut oak
GRA	Green ash
HAW	Hawthorn
HZNT	Hazlenut
MUL	Mulberry
REO	Red oak
RIB	River birch
SUST	Sumac, staghorn
WHO	White oak
GRASSES	
OG1	Orchardgrass
RG1	Annual ryegrass
RT1	Red Top - common
SB2	Smooth brome-Beacon
TF2	Tall fescue-Fawn
LEGUMES	
AC1	Alsike-common
AL1	Alfalfa-Vernal
AL15	Alfalfa-Cargill Crown
BT1	Birdsfoot trefoil
LC1	Ladino-common
RC1	Red clover-common
ROW CROPS	
CO1	Corn-Pioneer 3377
CO17	Corn-GH 2572
MI1	Millet-Pearl
MI3	Millet-German
SO1	Soybeans-Williams
WH3	Wheat-Pioneer 2555
WH8	Wheat-Dynasty

Equipment fluids

Material variety codes
Fertilizers and lime

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

MISCELLANEOUS ITEMS

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

COMPUTATIONAL PROCEDURES

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

Labor cost
Materials cost
Equipment cost
Vendor charges

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

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

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

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

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

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

BOND TRACKING REPORTS

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

Table 5. Example of RODA agency report.

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

Calendar Year: 1990

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

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

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

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

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

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

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

CONCLUSIONS

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

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

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

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

Table 6. Example of RODA farm field history report.

COMPOSITE HISTORY OF FARM FIELDS TO DETERMINE ELEGIBILITY FOR BOND RELEASE

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

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

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

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

EXECUTIVE SUMMARY OF BOND RELEASE STATUS

Year: 1990
Mine: Delta

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

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

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

INTRODUCTION

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

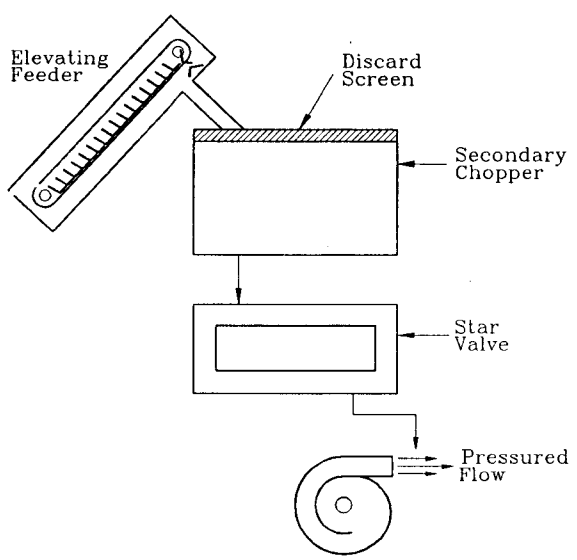
The conventional approach to preventing recompaction involves management practices aimed at minimizing the compactive effort applied to soil that has been deep tilled. Specially designed low ground pressure agricultural equipment has been used for this purpose.

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

OVERVIEW OF MODEL STUDY

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

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



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

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

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

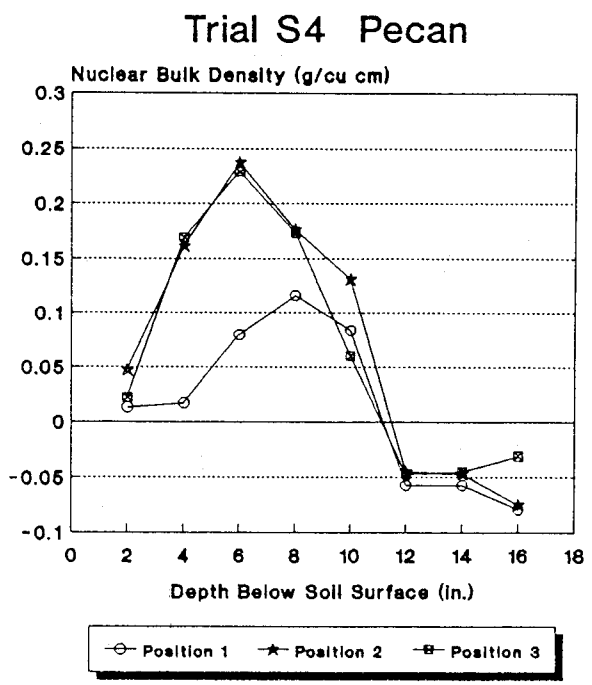
This method used a CPN Model MC-S-24 dual-probe nuclear density guage. The probes are separated by a distance of 12 inches. Measurements were taken within the ripped zone of the model at depth intervals of 2 inches from the surface downward to the maximum depth of penetration, which was approximately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

PROTOTYPE SOIL INJECTION SYSTEM DESIGN CONSIDERATIONS

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

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

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



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

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

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

BASIC COMPONENTS OF PROTOTYPE SYSTEM

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

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

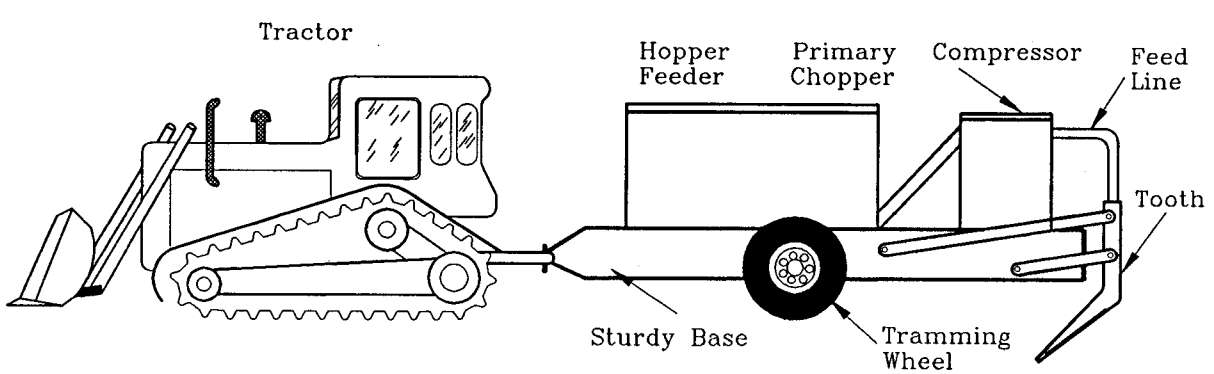
The least-capacity component will determine the maximum output of the system. Whether a feeder or a valve or whatever, all components will need to have the same throughput. Should that productivity be less than desired because of non-availability of larger components, then system speed or output or both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

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

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

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

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



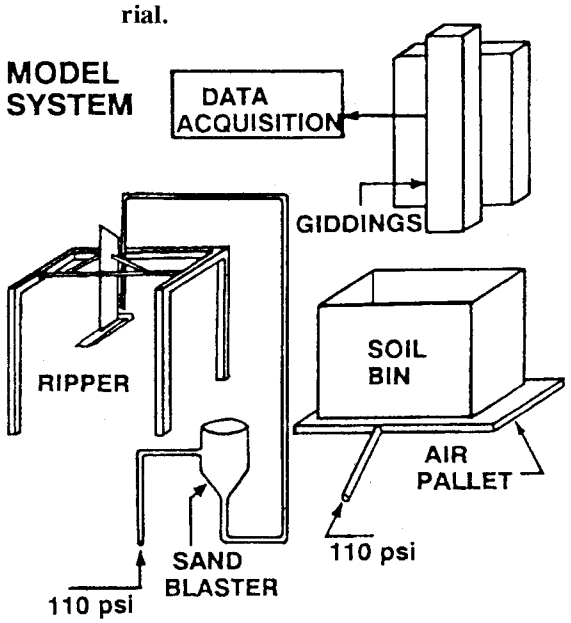
product is consolidated, for example round straw bales, then the hopper will need to be shaped so as to receive the product efficiently. An example of this is the round bale feeder, manufactured by Farmhand, Inc., which is also round and has a chopper built in.

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

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

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

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



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

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

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

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

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

VERIFICATION TRIALS FOR PROTOTYPE INJECTION SYSTEM

When a prototype injection system is built, it will be necessary to run a series of organized trials to (1) test the system, (2) verify the production rates that were assumed for the design, and (3) optimize the design of the subsoiler and its injection ports. While much of the system can be tested in the fabrication shop, the actual deposition of material can be tested only in field trials. Recognizing that there would be any number of frustra-

tions associated with inaugurating a new system, the tests recommended here are for a working prototype that has had the initial faults worked out.

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

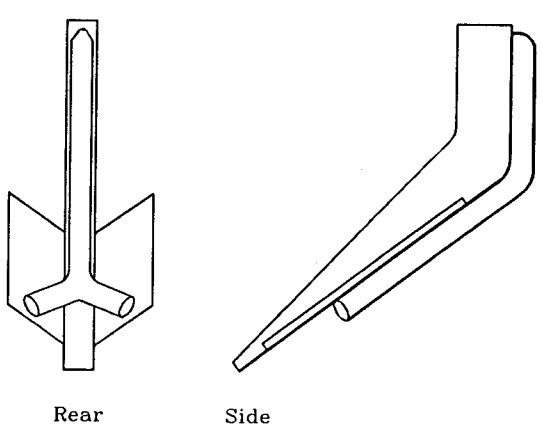
Each trial, therefore, should monitor continuously speed of the tractor and feed rates through the injector. Delays and their causes should be noted. Confirming measurements should be taken such as length of ripped zone and total amount of material injected. Additionally, turn times at the end of a row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

CONCLUSION

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

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

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



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Phosphorus Availability as Affected by Topsoil and Subsoil Mixing

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

INTRODUCTION

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

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

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

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

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

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

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

MATERIALS AND METHODS

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

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

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

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

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

RESULTS AND DISCUSSION

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

Effect of Wetting and Drying

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

Effect of Subsoil Mixing on Topsoil Properties

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

Table 1. Soil chemical characteristics prior to mixing.

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

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

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

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

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

[a] Averaged over the three P rates.

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

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

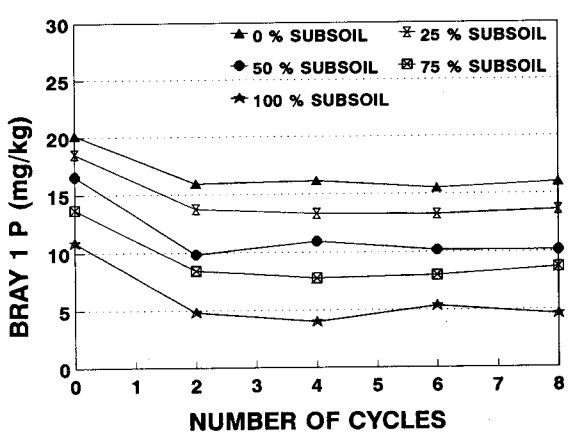


Figure 2. Variation in Mehlich III P due to wetting and drying of the various mixtures. Data averaged over three P rates.

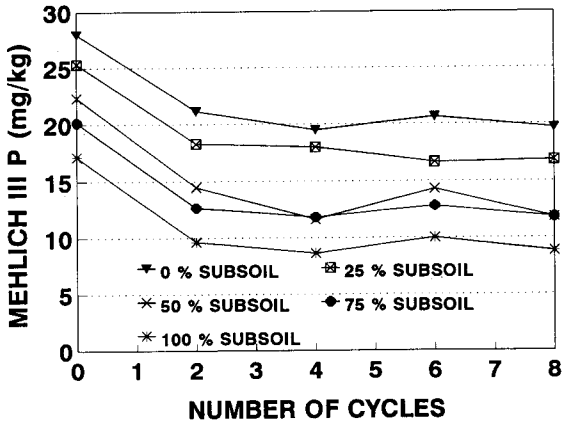


Figure 3. Variation in Bray 1P due to wetting and drying of the various mixtures using an acidic subsoil (SS-2). Data averaged over three P rates.

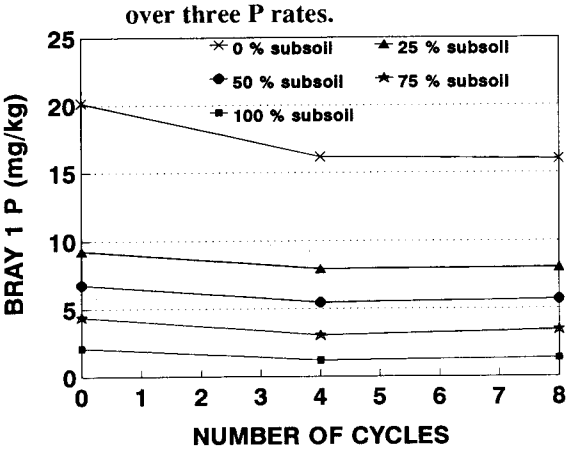
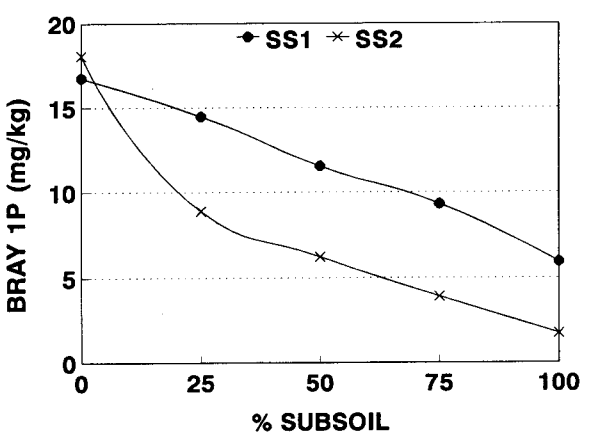


Figure 4. Available P as affected by topsoil and subsoil mixing. Data averaged over three P rates and eight wetting and drying cycles.



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

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

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

CONCLUSION

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

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Table 3. Summary of the analysis of variance

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

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

Sorbed P based on Bray 1 extractable P.

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

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

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

[a] Averaged across three P rates and eight cycles

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

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

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

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

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

INTRODUCTION

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

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

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

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

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

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

EXPERIMENTAL METHODS

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

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

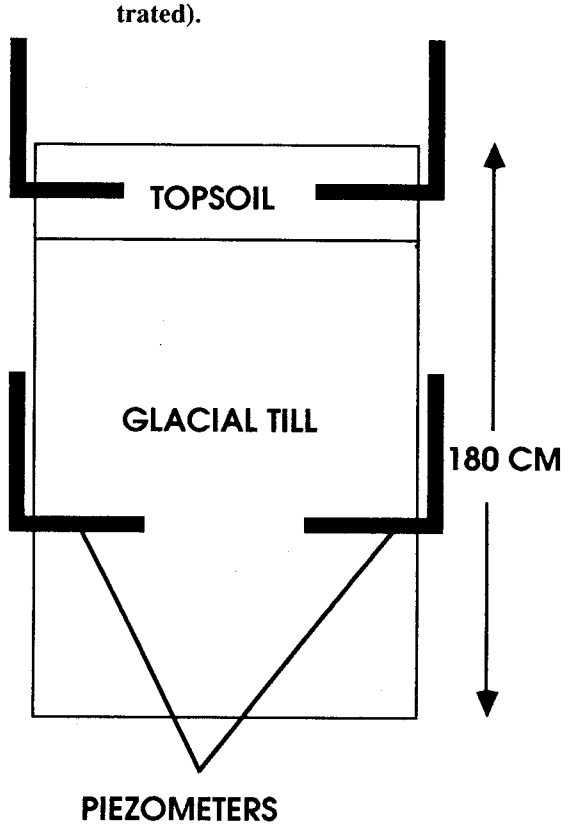
Lysimeters were constructed at the UMC Bradford Experimental Farm during the summer of 1988. Reclamation materials included topsoil, glacial till or subsoil, and FASS. Above-ground lysimeters (Fig 1.) 1.8 m deep by 1.2 m diameter were constructed from ribbed, spiral wrapped PVC pipe placed on a base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

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

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

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

Figure 1. Lysimeter design (control treatment illustrated).



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

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

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

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

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

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

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

RESULTS AND DISCUSSION

Reaction

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

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

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

Calcium Carbonate Equivalents

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

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

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

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

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

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

Major Elements

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

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

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

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

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

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

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

Minor Elements

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

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

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

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

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

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

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

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

Trace Elements

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

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

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

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

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

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

Soil Properties

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

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

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

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

Table 5. Chemical properties of lysimeter materials.

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

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

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

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

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

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

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

Plant/Lysimeter Results

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

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

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

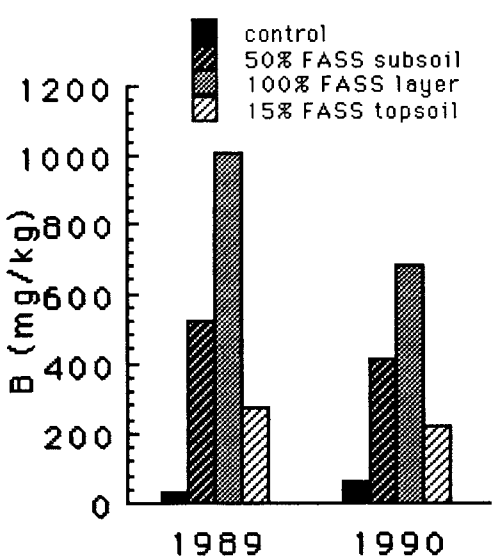
Treatment	1989	1990
	----- kg ha^{-1} -----	
control	5965	6501
50% FASS in subsoil	3185	5927
100% FASS in layer	3005	5130
15% FASS in topsoil	4652	7548

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

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

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

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

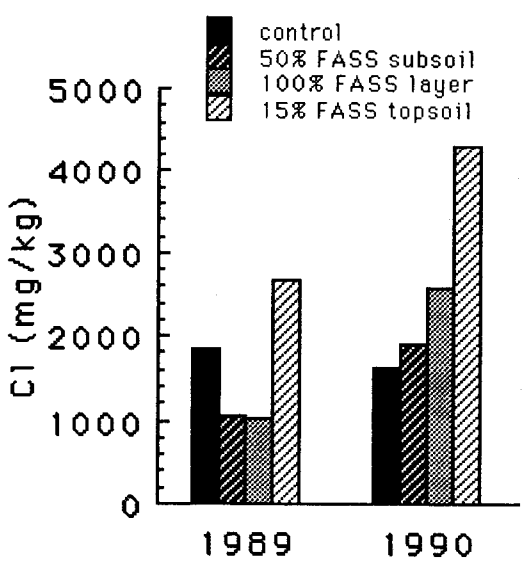


Mean alfalfa control leaf B was 61 mg/kg in 1990, as opposed to 33 mg/kg in 1989. Mean leaf B concentrations resulting from FASS addition followed the same pattern as in 1989, but levels were reduced by approximately 20 to 30 percent. Given the marked improvement in the appearance of the 1990 crop, lower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

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

Boron toxicity effects in soybeans were most severe when 15% FASS was incorporated into the topsoil. Soybeans on two lysimeters so treated suffered 100% mortality within eight weeks of planting. Soybeans do not root so deeply as alfalfa and the severity of phytotoxicity in this treatment is attributed to the majority of the rooting volume occurring in the upper 30 cm of the lysimeter and being in direct contact with the FASS/topsoil mixture.

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



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

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

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

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

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

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

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

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

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

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

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

RECOMMENDATIONS

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

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

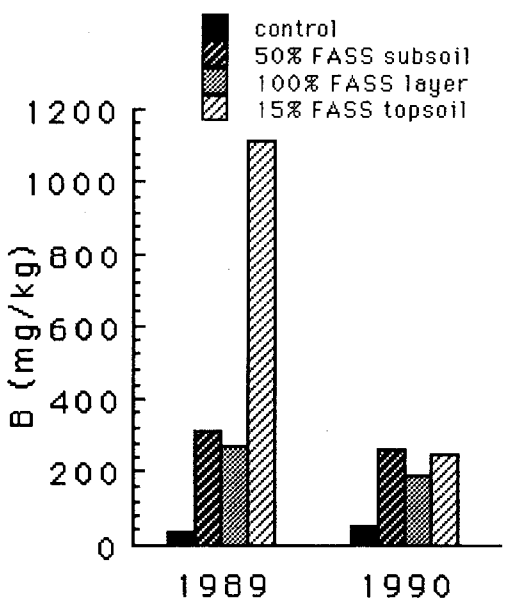
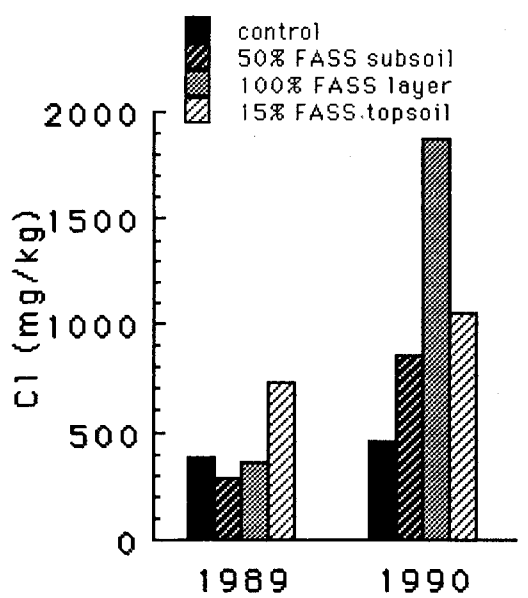


Figure 5. Effects of FASS on soybean leaf Cl content.



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

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

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

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

Tons/acre = 1800 * (100/fines %) * (3.0/ B content)

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

1800*(100/100)*(3.0/70) = 77.1 tons/acre ft (4.3% by weight)

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

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

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

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

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

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

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

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Fly Ash Scrubber Sludge Addition and Growth of Legumes and Grasses

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

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

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

INTRODUCTION

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

EXPERIMENTAL METHODS

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

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

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

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

RESULTS AND DISCUSSION

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

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

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

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

FASS has high water-holding capacity (Fig. 1). The moisture content at each pressure increased as the concentration of FASS in the soil increased. This is consistent with results of Chang et al. (1977) who found that fly ash added at 8% by weight significantly increased the soil water holding capacity. Since at -15 bar

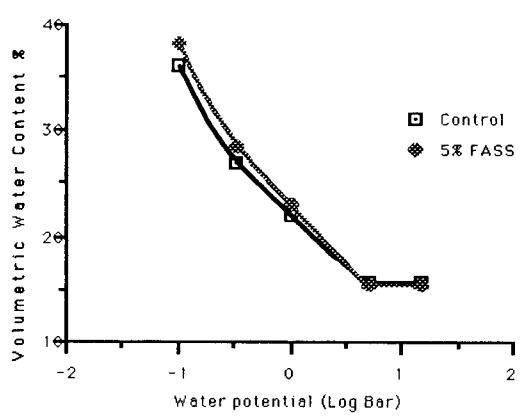
Table 1. Chemical properties of flyash scrubber sludge.

pH (0.01M CaCl2)		8.6
Calcium carbonate equivalence (%)		15
Total	Carbon (g kg^{-1})	7.5
	Aluminum (mg kg^{-1})	863
	Calcium " "	20040
	Iron " "	5933
Water soluble (1 to 1 extract)		mg kg-1
	Flouride	10.5
	Chloride	4270
	Nitrate	3.3
	Sulfate	2240
Hot water soluble Boron		261
Exchangeable (1M NH4Ac)		
	Calcium	8547
	Magnesium	227
	Potassium	354
	Sodium	274
DTPA Extractable		
	Copper	1.85
	Iron	64.5
	Manganese	6.0
	Zinc	3.6

Table 2. Chemical properties of flyash scrubber sludge-soil mixtures.

	SOIL	FASS 2.5%	FASS 5.0%
pHs (0.01M CaCl2)	5.1	5.7	6.2
Organic Matter %	2.1	2.0	2.0
Conductance dS m-1	1.65	2.83	3.36
Acidity cM kg-1	5.7	3.7	2.0
Bray No. 1 P mg P/kg	194	164	151
EXCHANGEABLE (1M NH4Ac)	- mg kg^{-1} -		
Calcium	2379	5670	8715
Magnesium	540	480	594
Potassium	348	340	345
Sodium	154	157	175
Chloride	——	25	39
Soluble Sulfate	331	641	689
Hot Water Soluble Boron	1.6	7.6	11.8

Figure 1. Water retention of soil and 5% FASS.



pressure the volumetric water contents of soil with and without 5% flyash are the same, increased field capacity moisture due to fly ash addition also increased available moisture (Fig. 2). Field capacity moisture was determined as the limit of capillary conductivity using the mudball technique and corresponds to a matrix pressure of about -0.7 bar.

Addition of FASS significantly increased the growth of alfalfa, birdsfoot trefoil, and fescue, and with significant effect on orchardgrass (Fig. 3). Yield differences between treatments of 2.5 and 5% FASS were not statistically significant for any plant species.

Concentrations of 2.5 and 5% FASS were chosen because in a preliminary study concentrations of 25 and 50% reduced germination and growth (unpublished data). It was concluded that both high Cl and B were factors reducing growth when FASS was applied at 25 and 50%.

Figure 2. Field capacity moisture content of soil, soil flyash mixtures, and flyash.

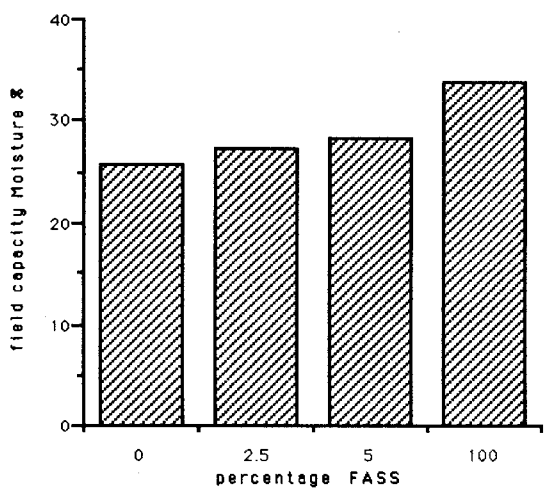
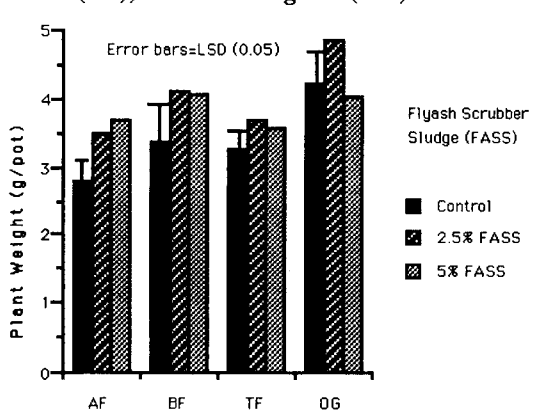


Figure 3. Effect of FASS on Growth of alfalfa (AF), birdsfoot trefoil (BF), tall fescue (TF), and orchardgrass (OG).



The concentrations of elements in the plant tissues were determined by ICP analysis of hydrogen peroxide and nitric acid digests of the tissues. Those elements whose concentrations were below the detection limit of the instrument are given along with the detection limits in Table 3.

Mean concentrations of elements whose concentrations in plants were not significantly changed by FASS addition are shown in Table 4.

FASS addition had no effect or slightly decreased the concentrations of Ca, Cd, Cu, K, Mg, Na, Ni, P, Ti, and Zn in alfalfa and birdsfoot trefoil stems and leaves and in the whole plant tissue of fescue and orchardgrass (Table 4). Calcium, Mg, and Cd concentrations of leaves of both alfalfa and birdsfoot trefoil were higher than in stems (Table 4). Phosphorus concentrations in

Table 3. Summary of elements that were below the detection limit of the ICP unit.

ELEMENT	Detection Limit
	mg kg^{-1}
Antimony	4.0
Arsenic	4.0
Beryllium	0.1
Bismuth	4.0
Chromium	1.0
Cobalt	1.0
Lead	4.0
Lithium	0.2
Selenium	5.0
Silver	1.0
Thallium	4.0
Tin	4.0
Tungsten	1.0
Vanadium	0.3

Table 4. Mean elemental Concentration in alfalfa (AF), birdsfoot trefoil (BF), tall fescue (TF), and orchardgrass (OG) that were not changed due to FASS addition.

Element	AF		BF		TF	OG
	stem	leaf	stem	leaf	entire	plant
			%			
Ca	0.93	2.23	0.58	1.64	0.60	0.48
K	3.32	3.09	3.70	3.40	4.70	5.55
Mg	0.18	0.39	0.17	0.41	0.38	0.27
P	0.55	0.37	0.58	0.28	0.48	0.52
			mg/kg			
Cd	0.7	1.9	1.1	1.4	1.0	0.5
Cu	13	15	11	11	13	20
Na	174	150	58	92	388	270
Ni	3.6	3.6	4.3	5.8	3.2	3.1
Ti	6.8	5.3	3.8	3.6	3.0	4.4
Zn	19	30	44	44	40	39

stems of alfalfa and birdsfoot trefoil were higher than in leaves. These elemental distributions between stems and leaves are consistent with those reported in the text by Mengel and Kirkby (1987b).

FASS addition significantly decreased Al (Fig. 4). The decrease in Al concentration is attributed to increased pH associated with FASS addition (Table 2). Decrease Al concentration in legumes may contribute to better symbiotic nitrogen assimulation (Tisdale et al., 1985b).

Ba (Fig. 5) and Sr (Fig. 6) concentration were also significantly reduced due to FASS addition. Decreased concentrations of Ba in plant tissue due to FASS addition may in part be due to decreased Ba solubility in soil associated with increased sulfate added with FASS (Table 1 and 2).

In every case, increasing the amount of FASS added to the soil decreased the concentration of Sr in plant tissue (Fig. 6). Decreased concentrations of Sr in plants may be due to Ca added with FASS and the associated dilution by Ca during the uptake process (Mengle and Kirby, 1987b).

Figure 4. Al concentration in AF, BF, TF, and OG.

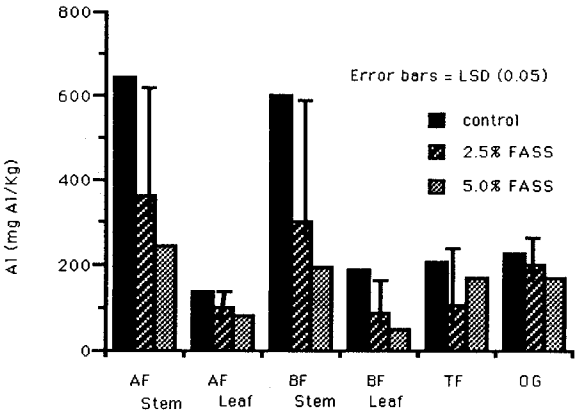
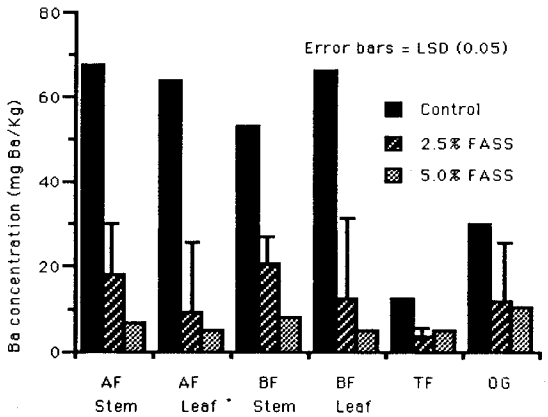


Figure 5. Ba concentration in AF, BF, TF, and OG.



Iron concentrations in alfalfa and birdsfoot trefoil were reduced due to FASS addition (Fig. 7). Decreases in Fe concentration in alfalfa and birdsfoot trefoil would be expected as pH increased due to FASS addition. However, the same decrease was not observed in Fe concentration for fescue and orchardgrass (Fig. 7). The reduction in Fe concentration in alfalfa and birdsfoot trefoil stems was greater than in leaves.

Concentrations of Mn, Mo, B, Cl and S were all increased by FASS addition. Concentrations of Mn are shown in Fig. 8. Increased Mn concentration in alfalfa and birdsfoot trefoil leaves and in fescue and orchardgrass grass with FASS addition was not expected. However the concentrations are in a range considered normal (Ohki, 1981).

Molybdenum availability is predicted to increase as pH increases (Stout et al., 1951). FASS addition increased pH and Mo as shown in Fig. 9.

Figure 6. Sr concentration in AF, BF, TF, and OG.

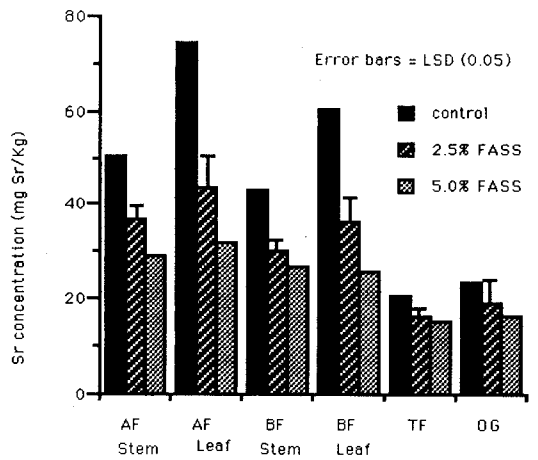
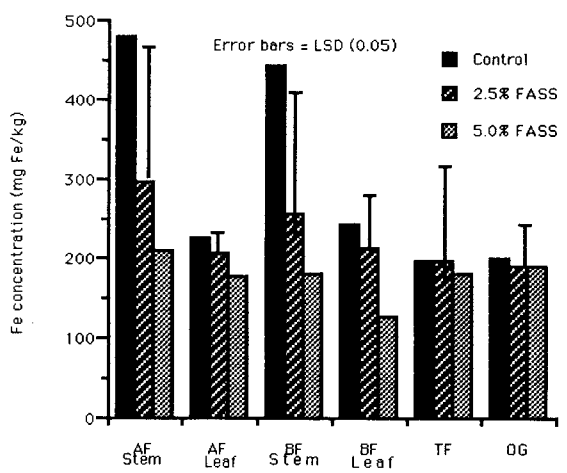


Figure 7. Fe concentration in AF, BF, TF, and OG.



Boron appeared to be one of the factors limiting the amount of FASS that could be added to soil. Data presented in Fig. 10 show the dramatic increases in B concentration in plant tissues due to FASS addition. Boron concentrations in the leaves of alfalfa and birdsfoot trefoil and in fescue and orchardgrass are high enough to be of concern, particularly at the 5% FASS concentration (Mengle and Kirkby, 1987a).

Figure 8. Mn concentration in AF, BF, TF, and OG.

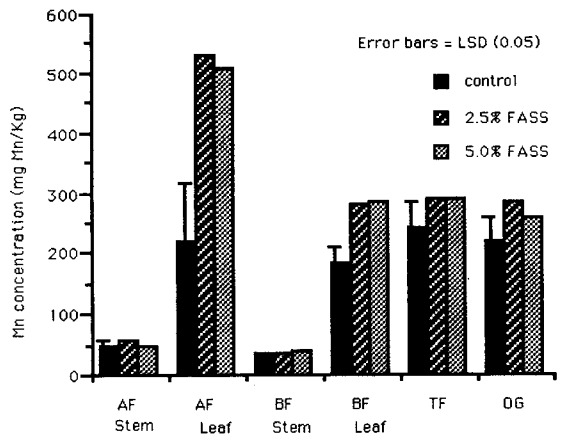


Figure 9. Mo concentration in AF, BF, TF, and OG.

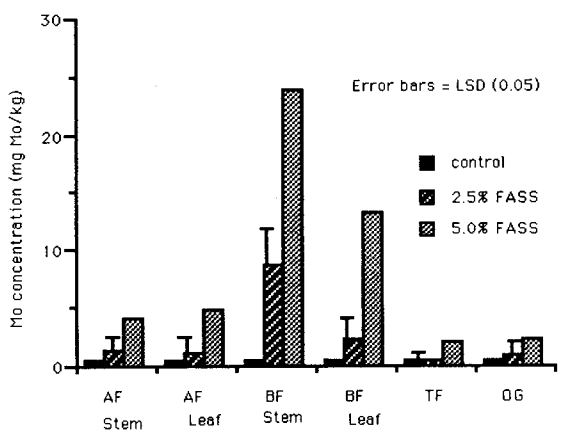
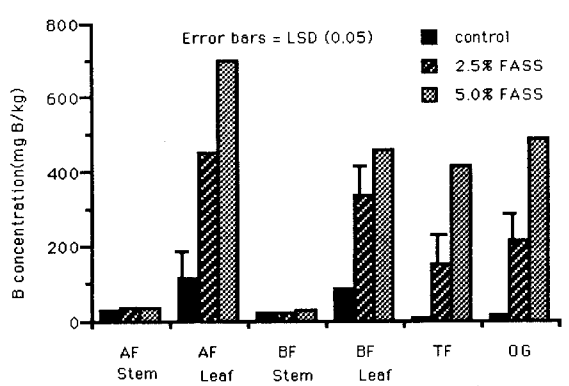


Figure 10. B concentration in AF, BF, TF, and OG.



Chloride concentrations were also increased due to FASS addition (Fig. 11). Chloride concentrations (Table 2) in the range of 0 to 40 mg kg^{-1} are not normally thought to reduce growth (Tisdale et al., 1985a). The data suggest boron rather than chloride may limit the amounts of FASS that can be applied to soil.

Increased S added with FASS shown in Fig. 12 may be beneficial to growth. Levels of S less than 1% have not been reported to be detrimental to plant growth. The S added with FASS should be considered an asset. Plant composition changes observed in this study are consistent with those that would be predicted due to additions with FASS or with changes in soil pH.

SUMMARY

Preliminary studies where FASS was added to soil in amounts of 25 and 50% (w/w) indicated severe damage to plants. Salt damage was severe and most plants died. The soil was leached to remove excess salts and in this case the plants grown at 50% FASS died due to B toxicity. At 25% FASS B toxicity reduced growth to less than a quarter of that on the control soil. It appeared that salt and B were going to limit the amount of FASS that could be added to soil.

Figure 11. Cl concentration in AF, BF, TF, and OG.

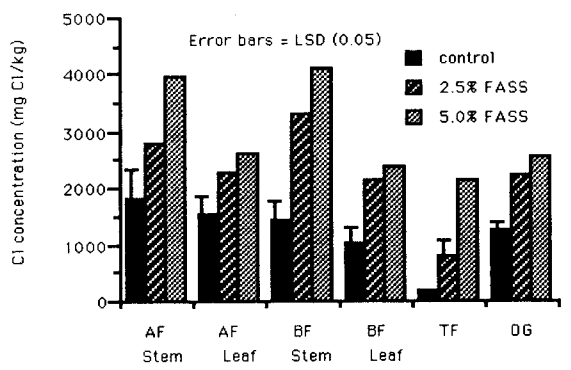
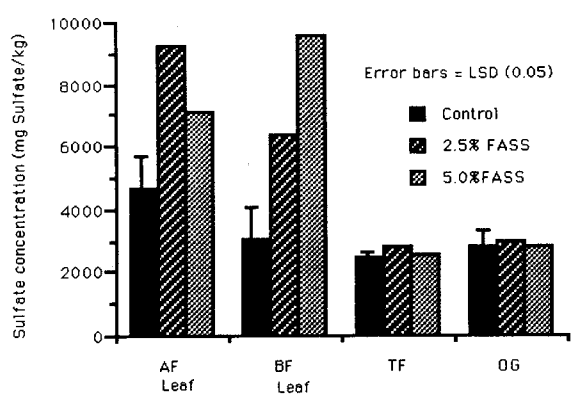


Figure 12. Sulfate concentration in AF, BF, TF, and OG.



Alfalfa, birdsfoot trefoil, tall fescue, and orchardgrass were grown in soils to which 0, 2.5 and 5% FASS was added. Alfalfa, birdsfoot trefoil, and fescue growth was increased due to the addition of 2.5% FASS, while orchardgrass was not significantly changed. Addition of 5% FASS resulted in salt levels in the soil predicted to be harmful to salt sensitive plants.

FASS addition either decreased or had no significant effect on the concentrations of the 35 elements in the various plant tissues. In the case of the heavy metals this was attributed to increased pH due FASS addition. B, Mn, Mo, Cl and S concentrations were increased due to FASS addition. Increases of B, Cl and S are probably due to the large amount added with FASS. Higher Mo may be due to increased availability with increased pH. No explanation is offered for increased Mn content in the plant with increased FASS.

FASS has soil amendment properties which suggest that it may be beneficial to plant growth under some conditions. Improved water retention, pH, Ca, S and at low concentrations B are beneficial aspects. At high concentrations of FASS salt and B become limiting factors and may be harmful to plants.

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Effect of Nitrogen, Phosphorous and Potassium on Yield and Leaf Composition of Corn Grown on Scraper Placed Mine Soil

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Abstract. Response of corn grown on scraper placed soil media to annual applications of selected rates and combinations of N, P, and K was measured at the Denmark mine site in southern Illinois. Rates of N, P, and K ranged from 0 - 200 lbs/a, 0 - 80 lbs/a and 0 - 120 lbs/a, respectively. Treatment combinations were arranged to conform to a modified central composite design where treatments were randomized in three replications of a randomized complete block design. Ten to 12 random leaf samples were obtained from each plot (30 ft x 40 ft) each year at early silking (approximately R1) and yield estimates were obtained at maturity.

As expected the effects of N, P and K upon yield and chemical composition varied from year to year. In 1988, there was a significant N linear x P linear interaction that affected corn yield. Fertility variables did not significantly affect corn yields in 1989 or 1990. Nitrogen fertilizer was the most frequent element affecting leaf composition, but the effect was not consistent each year.

In general, corn yields in this study have been lower than those frequently observed on natural soils, suggesting that other factors such as moisture stress may have limited crop yield and, perhaps, response to fertilizer variables. Although some of the variation in chemical composition of the corn leaf in any particular year could be attributed to one or more fertility variables, the concentration of plant nutrients in the leaf was generally sufficient for higher yields than those observed. Corn yield and/or leaf composition was affected by one or more fertilizer variables each year of this study and fertilizer applications should be considered as a necessary part of the management of reclaimed soils for crop production. However, other management or climatic factors may also influence corn yields and affect response to fertility variables.

INTRODUCTION

Response of corn (Zea maize) to N, P and K fertilizer has been measured in innumerable experiments in the twentieth century. However, relatively few experiments have been conducted evaluating response on reclaimed minesoils. Dancer (7) found that more extractable P was required in minespoil to support maximum corn production than was required for topsoil. In some areas P is often deficient for revegetation, but K is usually sufficient (8). Others have found that P rates may need upward revision for wheat grown on minespoil but no revisions were needed for corn silage production (3). Sutton and Dick (16) indicated that establishment of vegetation on mined lands was often hindered by low availability of plant nutrients and soil moisture. In many cases the limiting fertility factor was soil acidity. In a study of corn yield response to a factorial arrangement of P and K rates, Barnhisel and Semalulu (2) observed a linear corn yield response to K at one location and a quadratic K response and a linear P x linear K response at another location. Corn leaf nutrient response to fertility rates also varied between locations. Various factors including different soil construction methods may have contributed to the differential responses.

It has been established that different soil construction methods studied in Illinois affect soil physical properties and subsequent crop yield when compared to natural soils (9,10). McSweeney et al., (9) found that minesoils built with scrapers produced less corn and soybeans than soils constructed by other methods. The scraper system produced a more compact subsoil which limited root development and plant-available moisture. Stucky and Lindsay (15) studied the effect of compaction upon soybean growth and yield. They reported that in all instances plants grown on soil compacted to a bulk density of 1.4 g/cm^3 outyielded those grown on soil compacted to 1.6 g/cm^3. Barnes et al., (1) reported the development of compact layers in reconstructed soils

due to repetitive trips by scrapers. They indicated that the adverse effect varied due to soil media texture, moisture content and machinery traffic. Wolkowski (18) indicated that the effects of compaction might result in a decrease in N availability and reduction in K uptake due to lower root respiration. He also indicated that fertilization may compensate partially for yield limitation. McFee et al., (11) reported that N, P, and K were less effective than sludge, but usually produced increased plant growth.

Soil media characteristics other than plant nutrients may have received more emphasis due to the severe effects of compaction on crop growth and yield. Some research has been conducted evaluating soil fertility and soil test methodology as it relates to reclaimed minesoil (4,5,7). It has been suggested that plant nutrient research on reclaimed land should be at two or three rates and they should represent a broad range of application so that results can be plotted as nutrient response curves (8).

The objective of this research was to evaluate corn yield and leaf composition response to various rates and combinations of N, P, and K on scraper placed soil media.

MATERIALS AND METHODS

The experimental site was located at the Denmark mine in Perry county in southern Illinois. The mine soil at this site consists of 8 inches of scraper-placed topsoil over 40 inches of scraper placed rooting media. The area was deep tilled to a depth of approximately 32 inches in 1985 using the Kaeble-Gmeinder TLG-12. Experimental plots were 20 ft x 30 ft and planted to eight rows of corn. In 1988 and 1989 the hybrid planted was LH119xLH51 and in 1990 an early maturing hybrid (FS6566) was selected due to late planting.

It was assumed in this study that a quadratic polynomial was sufficient to characterize corn yield and other parameters of interest. Thus, fertilizer rates and combinations were selected to conform to a modified central composite design (6). Twenty - three treatment combinations of N, P and K were randomized in three replications of a randomized complete block design. Fertilizer rates and combinations were broadcast annually and disced prior to planting. After the first year (1988) fertilizer effects consist of response to the annual application plus residual effects. At approximately the early silking stage of development (R1) 10 - 15 randomly selected leaf samples were taken from each plot, dried, and sent to Brookside Farms Laboratories for determination of leaf levels of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn and Zn. Fertilizer sources of N, P, and K were ammonium nitrate, superphosphate and muriate of potash.

Soil samples were obtained from each plot each year and analyzed for pH, P and K by Brookside Farms Laboratories, which use the Mehlich 3 extractant and values were adjusted to Bray P1 and ammonium acetate extractable K. At the initiation of the experiment, soil pH, P and K averaged 6.5, 28 lb/a, and 136 lb/a, respectively. Soil pH ranged from 4.8 to 7.6, soil P ranged from 19 to 42 lb/a and soil K ranged from 112 to 256 lb/a. Agricultural limestone was applied to individual plots to adjust soil pH prior to planting in 1988.

RESULTS AND DISCUSSION

1988

Corn was seeded on May 5 at a rate of 23,200 seeds per acre under dry soil conditions. Emergence and stand establishment was characterized as good to very good. Precipitation in May was well below normal, and droughty conditions continued through the month of June. Severe early season stress symptoms were observed on all plots. Total rainfall for the month of June was only 1.7 inches coupled with above normal temperatures. The average maximum temperature for the entire months of June, July, and August exceeded 90° F each day. Late July rainfall aided pollination, but weather stress undoubtebly affected yield response.

Treatment means and results of the analysis of variance for 1988 are presented in Tables 1 and 2. Corn yield was significantly effected by both N and P fertilizer and the response is illustrated in Fig. 1. Yield response to N was greater at lower levels of P, and response leveled off at about 150 lb/a. Percent N in the corn leaf increased linearly within the rates of N used in this experiment (Fig. 2). Leaf percent K increased in the as rate of K increased and the effect was enhanced at higher rates of N (Fig. 3). Leaf Mg was also affected by N and K rates (Fig. 4) and the K effect was increasingly negative as rate of N increased (Fig. 4). Walker and

Figure 1. Corn yield response to N at two P rates (1988).

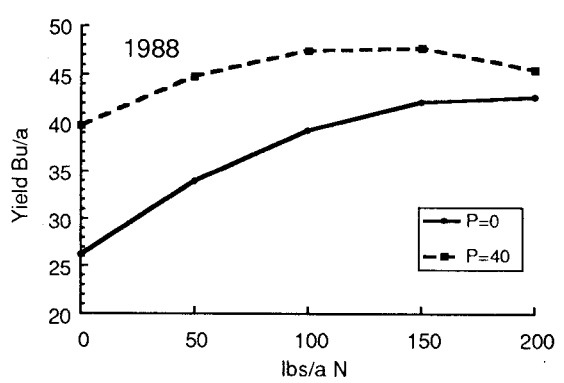


Table 1. Treatments, average corn yield and leaf composition from the Denmark Fertility Experiment, 1988.

Fertilizer Treatment	Trt#	Reps	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
N P K			Percent						Parts per Million					Bu/a
050-20-030[1/]	1	3	2.37	0.24	1.69	0.54	0.42	0.25	22.2	156.9	178.6	9.2	55.6	50.4
050-20-090	2	3	2.44	0.26	1.78	0.55	0.40	0.25	28.3	149.2	127.6	15.0	34.8	27.9
050-60-030	3	3	2.28	0.24	1.75	0.57	0.40	0.27	24.8	149.2	168.7	10.9	30.6	53.5
050-60-090	4	3	2.51	0.28	1.67	0.62	0.46	0.34	27.7	144.5	150.8	14.2	41.2	52.6
150-20-030	5	3	2.64	0.26	1.43	0.58	0.50	0.34	25.7	142.2	111.2	13.7	42.5	46.3
150-20-090	6	3	2.70	0.25	1.53	0.60	0.52	0.36	25.8	170.0	165.5	13.9	44.0	39.6
150-60-030	7	3	2.52	0.25	1.46	0.57	0.46	0.31	24.7	160.8	153.2	10.8	41.8	46.6
150-60-090	8	3	2.70	0.25	1.86	0.50	0.38	0.30	25.4	158.1	191.7	11.3	45.9	49.1
100-40-060	9	3	2.80	0.29	1.61	0.61	0.49	0.34	30.2	153.3	131.9	13.2	40.4	40.3
000-40-060	10	3	2.15	0.24	1.53	0.61	0.40	0.38	28.1	137.9	123.3	14.7	33.3	35.1
200-40-060	11	3	2.83	0.29	1.68	0.56	0.48	0.34	27.2	167.8	152.5	12.4	45.8	51.3
100-00-060	12	3	2.43	0.24	1.99	0.42	0.34	0.27	24.0	145.4	146.4	11.3	47.9	33.5
100-80-060	13	3	2.60	0.26	1.60	0.59	0.44	0.28	27.5	162.9	126.7	15.2	37.2	59.4
100-40-000	14	3	2.64	0.26	1.59	0.54	0.46	0.37	26.5	168.7	204.3	17.0	47.9	56.1
100-40-120	15	3	2.45	0.24	1.82	0.50	0.37	0.25	29.0	145.8	162.5	11.0	40.3	46.2
000-00-000	16	3	2.02	0.23	1.58	0.47	0.32	0.35	27.9	164.0	125.2	14.5	34.9	27.3
000-00-120	17	3	2.03	0.22	1.76	0.53	0.32	0.27	27.4	130.6	131.5	19.6	25.4	30.5
000-80-000	18	3	2.05	0.23	1.63	0.51	0.34	0.30	26.3	133.3	169.8	10.7	29.3	47.4
000-80-120	19	3	2.14	0.26	1.72	0.56	0.35	0.27	28.6	126.5	113.7	9.3	27.4	49.3
200-00-000	20	3	2.58	0.26	1.44	0.62	0.60	0.44	27.6	160.5	176.4	14.4	59.9	41.2
200-00-120	21	3	2.59	0.26	1.89	0.47	0.40	0.24	24.4	164.5	136.1	12.9	47.4	47.3
200-80-000	22	3	2.77	0.27	1.36	0.63	0.55	0.39	27.0	161.2	120.8	14.6	40.9	33.7
200-80-120	23	3	2.97	0.27	1.80	0.49	0.41	0.31	28.9	194.0	185.3	17.4	48.6	48.0

[1/] Fertilizer treatments are lbs/acre of elemental nitrogen, phosphorous, and potassium, respectively.

Table 2. Error mean squares and F ratios measuring the effect of fertilizer rates upon corn yield and leaf composition on the Denmark Fertility Experiment, 1988.

Sources of Variation	DF	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
		F Ratio											
Total	68												
Blocks	2	13.21*	7.10**	12.97**	10.36**	23.92**	15.69**	0.35	4.28*	7.35**	0.17	6.17**	5.65**
Treatments	22												
N Linear	1	7.17*	0.45	0.54	0.01	1.72	0.94	0.32	0.01	0.83	0.66	4.05*	3.03+
P Linear	1	0.57	2.73	2.12	2.33	2.11	0.72	0.14	0.54	1.59	0.84	0.34	2.38
K Linear	1	0.13	0.93	0.15	1.37	0.37	0.17	0.17	1.85	5.22*	0.05	1.33	0.62
N Quadratic	1	1.67	0.54	2.58	0.73	0.26	2.45	0.22	0.06	1.47	0.12	1.16	1.47
P Quadratic	1	0.91	1.71	2.10	1.38	1.65	1.51	0.39	0.01	1.70	0.01	0.38	0.25
K Quadratic	1	0.26	0.79	0.01	0.60	0.29	0.01	0.30	0.12	3.32*	0.43	0.07	0.27
N*P Linear	1	1.19	1.01	0.11	0.10	0.56	0.15	0.29	3.28+	0.01	7.21*	0.21	4.34*
N*K Linear	1	0.08	1.32	5.34*	4.70*	5.33*	1.17	0.22	5.09*	2.99+	0.31	0.56	0.49
P*K Linear	1	0.78	0.81	0.01	0.09	0.01	0.72	0.69	1.80	0.15	0.19	3.63+	0.20
Residual MS	13	0.3288	0.0013	0.096	0.0057	0.0174	0.0079	12.121	727.413	998.699	21.53	231.69	229.17
Error MS	44	0.0498	0.0005	0.321	0.0114	0.0072	0.0074	23.192	475.508	1803.188	15.20	89.15	169.24

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

Figure 2. Response of leaf N to rate of N (1988).

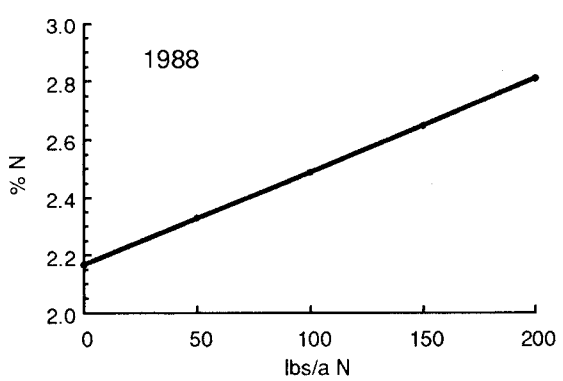
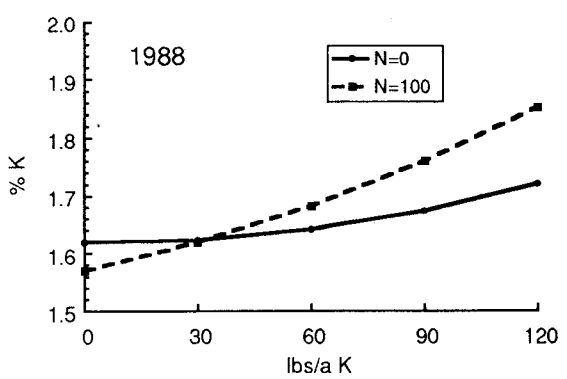


Figure 3. Response of leaf K to rate of K at two N rates (1988).



Peck (17) also reported a negative K effect upon corn leaf Mg in southern Illinois. Leaf Cu was affected by both N and P rates (Fig. 5).

1989

Corn was planted on May 6 under very favorable soil moisture conditions. Subsequent rainfall aided emergence and stand establishment. Below normal precipitation and above normal temperatures characterized the late June and early July growing period. Rain in mid-July aided pollination, but very high temperatures and below normal rainfall in the late-July to mid-August growing season resulted in visible stress symptoms appearing on all plots.

Treatment means and analysis of variance results for 1989 are presented in Tables 3 and 4. Fertility treatments did not significantly affect corn yield in 1989, but did significantly affect leaf composition. Leaf N increased with increasing rates of N (Fig. 6) and values observed were somewhat higher than those observed in 1988. Leaf P increased with increasing levels of P, but the effect was greater at low N rates (Fig. 7). Both N and P had a more significant effect upon leaf K in 1989 than did fertilizer K (Table 4). The effects of N and P are illustrated in Fig. 8 which shows that maximum leaf K occured at about 100 lb/a of N. Leaf Cu was affected by P rate, but levels observed were adequate. Effects of N and P are illustrated in Fig. 9. Leaf Zn increased as N rate increased and there was a small negative effect of P upon leaf Zn (Fig. 10).

Figure 4. Response of leaf Mg to rate of K at two N rates (1988).

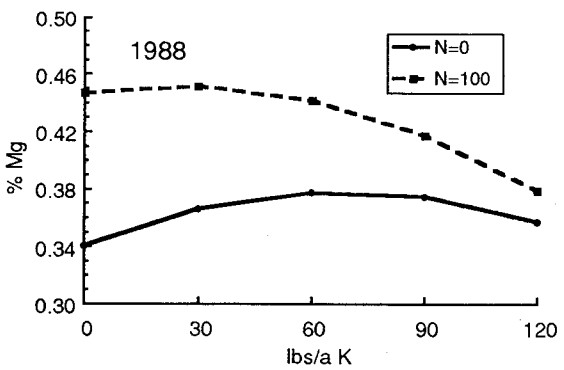


Figure 5. Response of leaf Cu to rate of P at two N rates (1988).

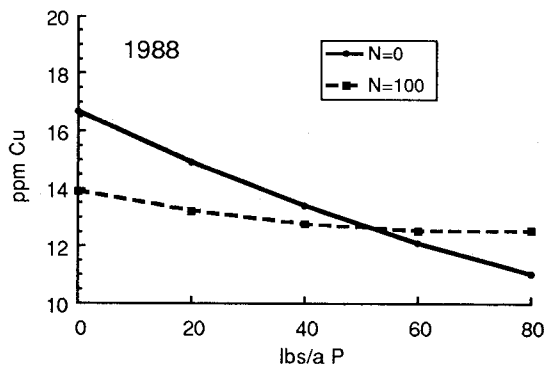


Table 3. Treatments, average corn yield and leaf composition from the Denmark fertility experiment, 1989.

Fertilizer Treatment	Trt#	Reps	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
N P K			Percent						Parts per Million					Bu/a
050-20-030[1/]	1	3	2.38	0.29	2.09	0.65	0.35	0.27	6.5	124.1	79.5	11.8	26.6	54.3
050-20-090	2	3	2.64	0.28	2.14	0.66	0.38	0.27	7.7	127.1	94.6	11.7	29.2	48.4
050-60-030	3	3	2.54	0.29	1.89	0.55	0.36	0.32	5.1	106.8	99.4	10.0	24.5	44.6
050-60-090	4	3	2.86	0.33	2.39	0.71	0.32	0.29	6.2	132.4	87.4	13.0	21.6	62.7
150-20-030	5	3	2.96	0.32	1.91	0.82	0.47	0.43	7.9	135.1	107.6	14.6	30.3	59.4
150-20-090	6	3	3.38	0.33	2.01	0.67	0.51	0.35	7.2	133.6	144.1	16.1	42.6	60.1
150-60-030	7	3	3.02	0.31	1.99	0.81	0.52	0.39	6.8	157.2	134.1	14.1	30.9	68.1
150-60-090	8	3	3.11	0.33	2.33	0.69	0.41	0.36	7.1	138.6	174.0	15.1	37.9	59.7
100-40-060	9	3	2.94	0.31	2.15	0.75	0.43	0.42	7.0	137.7	108.8	15.1	25.6	55.2
000-40-060	10	3	2.50	0.31	1.76	0.61	0.35	0.27	6.4	106.8	85.3	11.1	23.9	38.1
200-40-060	11	3	3.26	0.33	2.02	0.75	0.41	0.39	7.2	146.7	129.4	16.8	31.2	67.3
100-00-060	12	3	3.22	0.33	2.42	0.61	0.40	0.32	6.1	142.7	106.7	15.5	38.6	53.0
100-80-060	13	3	2.86	0.32	2.33	0.77	0.45	0.39	6.4	169.8	123.0	15.9	22.2	50.6
100-40-000	14	3	3.13	0.31	1.84	0.71	0.53	0.37	6.7	127.2	153.3	13.1	34.6	57.3
100-40-120	15	3	2.62	0.29	2.19	0.63	0.32	0.33	6.7	125.0	94.5	11.8	24.8	57.8
000-00-000	16	3	2.37	0.28	1.96	0.54	0.40	0.34	6.9	102.1	94.1	11.4	27.3	38.2
000-00-120	17	3	2.16	0.26	1.92	0.52	0.26	0.23	6.2	94.9	69.2	10.0	22.8	45.7
000-80-000	18	3	2.12	0.31	1.59	0.64	0.37	0.29	5.1	99.7	58.0	10.8	18.2	48.9
000-80-120	19	3	2.44	0.36	1.86	0.61	0.32	0.32	4.6	114.2	66.1	12.7	19.6	41.0
200-00-000	20	3	3.32	0.31	1.79	0.72	0.51	0.40	7.1	137.4	174.4	17.1	52.5	48.8
200-00-120	21	3	3.67	0.35	2.19	0.70	0.48	0.28	7.1	138.0	134.6	19.1	48.9	57.0
200-80-000	22	3	3.27	0.32	1.50	0.95	0.71	0.38	8.9	154.2	159.5	15.1	27.3	70.2
200-80-120	23	3	2.97	0.30	2.10	0.62	0.31	0.31	6.7	142.3	148.0	14.8	29.6	52.1

[1/] Fertilizer treatments are lbs/acre of elemental nitrogen, phosphorous, and potassium, respectively.

1990

Excessive spring rainfall resulted in delayed planting in 1990. Soils remained in a saturated condition until late June. A short season hybrid (FS6566) was substituted for the hybrid used in the previous years. The change in hybrids and late planting undoubtedly affected 1990 results. May precipitation was twice the average, June rainfall was near normal, but drier conditions prevailed in July and August with only 75% of normal rainfall.

Table 4. Error mean squares and F ratios measuring the effect of fertilizer rates upon corn yield and leaf composition on the Denmark Fertility Experiment, 1989.

Sources of Variation	DF	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
		F Ratio											
Total	68												
Blocks	2	1.97	0.12	2.62^{+}	5.04*	0.02	11.96**	2.29	1.54	1.68	4.10*	4.78*	17.88**
Treatments	22												
N Linear	1	6.33*	1.79	6.75*	2.57	4.02*	2.71	0.01	10.95**	6.79*	4.50*	3.75^{+}	2.27
P Linear	1	0.05	0.14	5.93*	0.78	0.02	0.01	0.01	3.05^{+}	0.21	2.86^{+}	1.29	1.84
K Linear	1	0.62	1.03	3.13^{+}	0.75	0.25	0.13	0.01	4.49*	1.89	2.89^{+}	0.44	0.10
N Quadratic	1	0.42	0.01	10.51**	0.09	0.52	0.77	0.06	4.33*	0.87	0.01	0.13	0.59
P Quadratic	1	0.17	0.59	3.55^{+}	0.02	0.16	0.02	0.61	4.63*	0.01	4.59*	0.34	0.92
K Quadratic	1	0.50	1.02	3.69^{+}	0.34	0.25	0.03	0.01	4.73*	0.75	3.59^{+}	0.13	0.05
N*P Linear	1	1.83	11.56**	0.09	0.03	0.01	0.12	3.72^{+}	0.17	1.22	5.17	4.35*	0.24
N*K Linear	1	0.01	0.02	2.68	3.25^{+}	2.18	0.66	0.40	0.85	0.13	0.10	0.22	0.37
P*K Linear	1	0.07	0.28	2.26	1.46	3.17^{+}	1.37	0.36	0.10	1.60	0.18	0.38	2.55
Residual MS	13	0.7465	0.0015	0.0765	0.4800	0.0400	0.0110	3.36	869.21	5229.14	20.98	339.59	272.76
Error MS	44	0.1678	0.0010	0.0723	0.0177	0.0112	0.0091	2.26	392.78	680.13	5.23	76.47	198.57

**, Statistically significant at the 0.01 level.
*, Statistically significant at the 0.05 level.
$^{+}$, Statistically significant at the 0.10 level.

Figure 6. Response of leaf N to rate of N (1989).

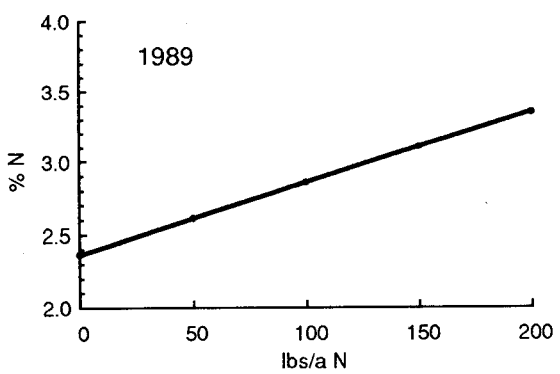


Figure 7. Response of leaf P to rate of P at two N rates (1989).

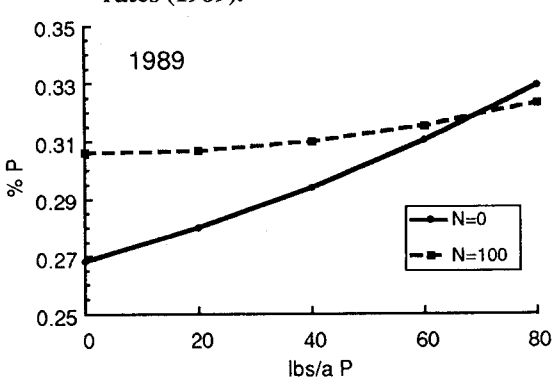


Figure 8. Response of leaf K to rate of N at two P rates (1989).

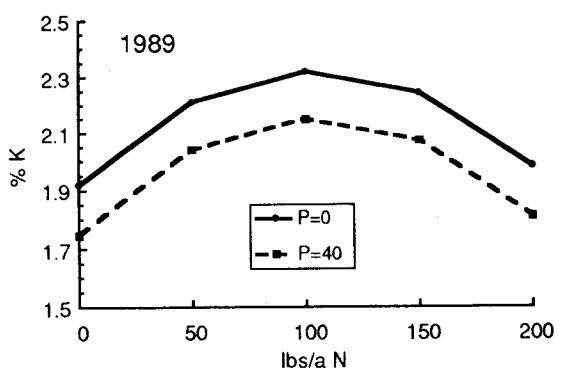


Figure 9. Response of leaf Cu to rate of P at two N rates (1989).

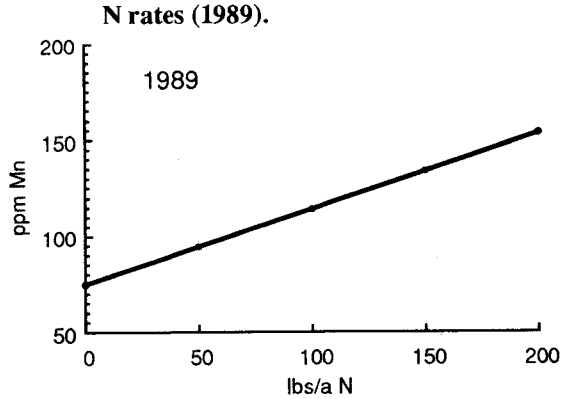
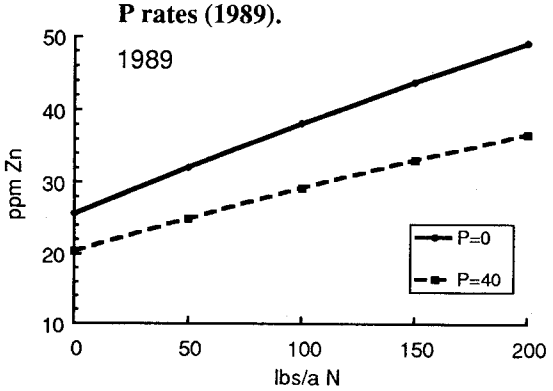


Figure 10. Response of leaf Zn to rate of N at two P rates (1989).



Treatment means and analysis of variance results for 1990 are presented in Tables 5 and 6. As in previous years leaf N was significantly affected by rate of N. However, in 1990 there was a significant quadratic effect and it is illustrated in Fig. 11 where leaf N reaches a maximum at about 150 lb/a of N. Phosphorus was the most significant variable affecting leaf K in 1990 and its effect is illustrated in Fig 12. Within the range of P applied leaf K did not vary greatly. Leaf Mg was affected by both N and K fertilizer and the effects are illustrated in Fig. 13. Leaf Mg decreased with increases in fertilizer K, the magnitude affected by rate of N. Leaf S was affected by each fertility variable in 1990 and the

Table 5. Treatments, average corn yield and leaf composition from the Denmark Fertility Experiment, 1990.

Fertilizer Treatment	Trt#	Reps	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
N P K			Percent						Parts per Million					Bu/a
050-20-030[1/]	1	3	2.58	0.31	1.97	0.66	0.30	0.24	9.7	239	74	13.2	41.1	54.7
050-20-090	2	3	2.59	0.28	2.01	0.80	0.36	0.25	10.8	236	94	13.7	35.8	57.1
050-60-030	3	3	2.26	0.28	1.83	0.69	0.34	0.27	9.0	204	92	11.5	37.0	66.3
050-60-090	4	3	2.76	0.32	1.83	0.83	0.38	0.23	8.6	215	86	13.3	34.8	56.7
150-20-030	5	3	3.36	0.31	1.67	0.84	0.39	0.26	10.9	220	104	16.3	40.6	68.7
150-20-090	6	3	3.05	0.27	1.67	0.68	0.28	0.29	11.0	224	103	15.6	37.4	68.5
150-60-030	7	3	3.30	0.34	1.96	0.82	0.44	0.28	10.0	225	104	15.5	43.6	76.9
150-60-090	8	3	3.07	0.28	1.59	0.67	0.27	0.25	10.1	232	125	17.6	60.9	39.1
100-40-060	9	3	3.13	0.31	1.95	0.74	0.26	0.27	11.5	228	102	17.3	36.8	60.9
000-40-060	10	3	2.38	0.31	1.99	1.09	0.59	0.27	14.7	214	134	14.5	31.5	53.9
200-40-060	11	3	3.37	0.31	1.93	0.83	0.34	0.25	13.1	215	123	17.0	46.5	73.5
100-00-060	12	3	3.34	0.30	2.06	0.63	0.28	0.28	11.2	211	107	17.6	61.2	81.0
100-80-060	13	3	2.88	0.30	1.91	0.62	0.25	0.23	11.2	224	86.2	12.9	34.7	54.3
100-40-000	14	3	2.86	0.28	1.40	0.77	0.45	0.37	9.5	219	120	14.1	50.3	64.9
100-40-120	15	3	3.39	0.31	1.84	0.72	0.24	0.25	9.9	226	98	16.1	43.6	41.0
000-00-000	16	3	2.16	0.29	2.01	0.46	0.22	0.20	8.0	187	58	8.9	29.0	63.0
000-00-120	17	3	1.82	0.24	1.88	0.50	0.18	0.17	8.2	141	33	16.4	27.9	52.7
000-80-000	18	3	1.80	.34	1.58	0.52	0.25	0.18	7.7	189	42	7.9	23.3	55.1
000-80-120	19	3	1.65	0.33	1.98	0.47	0.21	0.18	8.9	153	41	7.6	26.6	63.4
200-00-000	20	3	3.49	0.29	1.47	0.79	0.56	0.29	13.2	212	172	17.3	68.8	41.9
200-00-120	21	3	3.27	0.31	2.08	0.71	0.33	0.25	12.7	202	169	19.2	74.6	43.9
200-80-000	22	3	3.23	0.29	1.46	0.92	0.47	0.25	10.4	238	134	14.8	38.0	54.9
200-80-120	23	3	3.12	0.31	2.03	0.63	0.24	0.24	10.1	206	103	15.1	83.4	56.8

[1/] Fertilizer treatments are lbs/acre of elemental nitrogen, phosphorous, and potassium, respectively.

Table 6. Error mean squares and F ratios measuring the effect of fertilizer rates upon corn yield and leaf composition on the Denmark Fertility Experiment, 1990.

Sources of Variation	DF	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Yield
		F Ratio											
Total	68												
Blocks	2	0.03	2.53+	0.21	1.25	1.87	0.58	2.16	11.72**	0.50	2.58+	1.02	12.11**
Treatments	22												
N Linear	1	18.12**	0.03	0.82	1.51	2.35	20.42**	0.35	6.39*	4.46*	5.36*	1.53	0.01
P Linear	1	0.00	0.46	4.08*	6.82*	2.95+	3.33+	0.002	0.42	0.44	0.11	1.93	0.32
K Linear	1	0.11	0.35	3.12+	0.48	0.46	5.91*	3.26+	0.04	0.15	1.29	1.43	1.48
N Quadratic	1	5.56*	0.01	0.01	0.02	0.13	13.98**	0.70	5.55*	0.05	1.59	0.31	0.01
P Quadratic	1	0.45	0.01	2.41	6.30*	2.61	5.65*	0.01	0.51	0.45	0.02	0.71	0.19
K Quadratic	1	0.34	0.02	3.72+	0.07	0.35	3.24+	3.24+	0.09	0.07	0.05	0.47	2.67
N*P Linear	1	0.03	3.10+	0.64	0.01	1.88	0.16	1.97	0.34	2.34	0.45	0.05	0.19
N*K Linear	1	0.03	1.68	2.45	3.70+	7.80**	0.01	0.39	0.47	0.02	0.69	3.17+	0.01
P*K Linear	1	0.39	0.53	0.56	1.14	0.01	0.33	0.04	0.17	0.01	1.80	2.65	0.03
Residual MS	13	1.311	0.001	0.092	0.540	0.030	0.003	7.51	2036.0	5510.6	40.95	968.16	472.21
Error MS	44	0.164	0.001	0.091	0.024	0.010	0.001	5.39	1127.6	1260.9	13.51	329.15	409.76

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

effect of N and K are illustrated in Fig. 14. It is not apparent from the data why S should be affected by fertility variables in 1990 and not in other years. Differences in growing seasons and the change in hybrid are possibilities. The only variable affecting leaf Cu in 1990 was N fertilizer and the effect is linear (Fig. 14).

The average change in soil P and soil K as a result of fertilizer applications was determined by regressing the difference between plot soil P and soil K values in 1991 and those in 1988 (1991 values - 1988 values) upon the total amount of P and K fertilizer applied. The resulting linear regression coefficients had values of 0.362 and 0.256 for P and K, respectively. This indicates that for each lb/a of fertilizer P applied, a 0.362 lb/a increase in available P occurred, and for each lb/a of fertilizer K applied, a 0.256 lb/a increase in exchangeable K was observed in the minesoil. Peck et al., (14) found that 4 lb/a of fertilizer P was required to increase the Bray P-1 soil test by 1 lb/a in natural soils.

Figure 11. Response of leaf N to rate of N (1990).

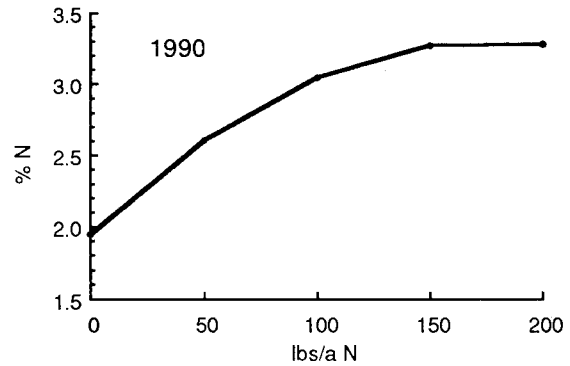


Figure 12. Response of leaf K to rate of P (1990).

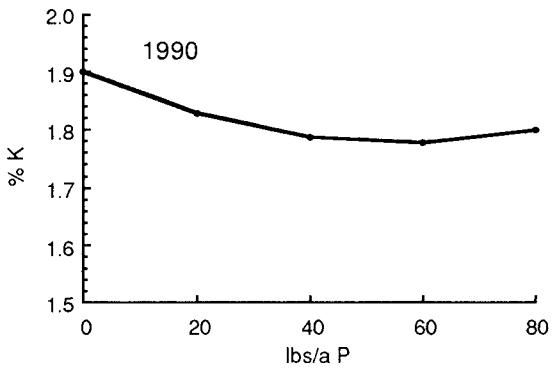
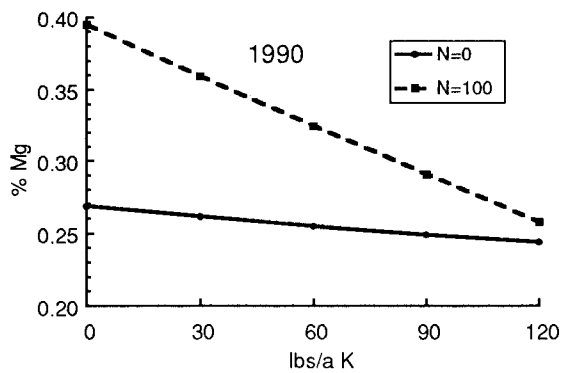


Figure 13. Response of leaf Mg to rate of K at two N rates (1990).



SUMMARY

Fertility variables significantly affected yield in 1988, but had no significant effect upon corn yield in 1989 and 1990. Fertility variables significantly affected leaf composition each year of the study, but effects were not consistent from year to year. Applied N was the variable most often associated with changes in leaf composition. Yields were lower than might have been expected on natural soils and it is likely that some factor(s) other than N, P and K were limiting. The leaf composition data indicate that plant nutrients were not major limiting factors at observed yields. The change in soil test levels of P as a result of applied P fertilizer indicate that the buildup in soil P in this study is similar

Figure 14. Response of leaf S to rate of N at two K rates (1990).

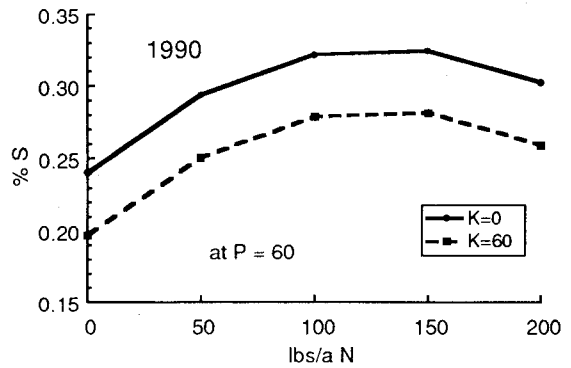
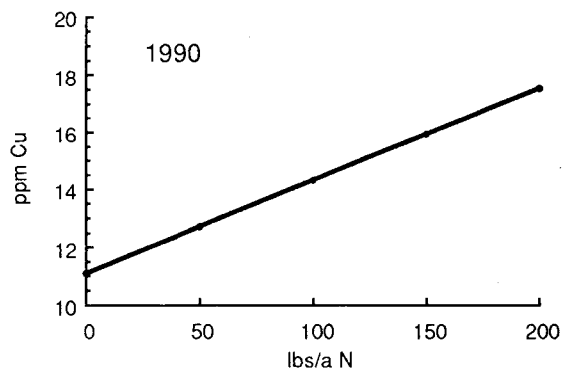


Figure 15. Response of leaf Cu to rate of N (1990).



to that observed in other studies on natural soils.

Corn yields at this site were low compared to those observed on nearby undisturbed soils. It is likely that soil compaction is a major factor limiting yields. Compaction alleviation with a tillage treatment deeper than that affected by the TLG-12 is probably necessary to achieve maximum response to fertility variables. It is probably unrealistic to expect a yield response to an increase in fertility in minesoil if factors such as soil moisture and plant root development are limiting.

ACKNOWLEDGEMENTS

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Row Crop Production in Iowa on Reclaimed Prime Farmland Soil

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Abstract. Since 1979, corn and soybeans have been grown on Clarion loam topsoil restored over its till substratum in Hamilton County, Iowa. The research was undertaken to determine the effect of restored topsoil depth on row crop productivity. Clarion loam (fine-loamy, mixed mesic Typic Hapludoll) was removed to a depth of 12 inches and stock-piled from the 7 1/2-acre site in 1976 in preparation for borrowing approximately 7 feet of subsoil and substratum materials to be used in highway roadbed construction. In 1978, 6 and 12 inches of topsoil were replaced in plots excavated to an equal depth into the substratum in three replicated blocks. A plot without replaced topsoil was also included in each block. The dimensions of experimental area are 360 x 400 feet and the area is 3.31 acres. Without topsoil replacement, corn production has achieved 33 percent of the yearly county average yield. Replacement of 6 and 12 inches of topsoil increased corn yields to 44 and 45 percent of the county average, respectively. Where no topsoil and 6 and 12 inches of topsoil were restored, soybeans have yielded 25, 46, and 52 percent of the county average, respectively. Plant diseases have been observed to be more severe in soybeans in the experimental area, especially where no topsoil was replaced, than on neighboring, undisturbed cropland. Climatic stress resulting from too little or too much moisture has accounted for reduced grain yields compared to county yields in all years and total crop failure in three years. The calculated productivity of this site has included the years where crop failures have occurred.

INTRODUCTION

This paper reports thirteen years of crop production at a site in northcentral Iowa where topsoil was restored following the removal of borrow for highway construction. The research work was supported by the Iowa Department of Transportation. The site was under construction during 1977 and 1978. Clarion loam (fine-loamy, mixed mesic Typic Hapludoll) topsoil occurring at 2 to 5 percent slope was removed to a depth of 6 to 12 inches and stockpiled before borrowing approximately 7 feet of subsoil and substratum materials. Before the last borrow was removed, research plots were planned so that three replicated blocks with three treatments each of restored topsoil could be constructed. These plots were cut to the depth equal to that of the topsoil to be restored; no topsoil, six inches and twelve inches. Each topsoil treatment was 40 feet wide and 400 feet long which yielded a research area that is 360 feet wide and 400 feet long or three and one-third acres. Topsoil restoration was completed in the September of 1978. A subsurface tile drainage system was installed following topsoil restoration. Four-inch diameter tile drainage tubes were installed on an 100-foot spacing, perpendicular to the long dimension of each plot. The research area and its border were fertilized with 100 pounds per acre each of nitrogen (N), phosphate (P_2O_5) and potash (K_2O), chisel plowed, disked, and planted to a winter wheat cover crop.

The substratum at the site is a basal calcareous till with a pH of 7.7. Although available phosphorus and potassium are generally low in the substratum, fertilization from 1978 to 1984 has provided adequate nutrients with current levels being rate high. The topsoil is alkaline with a pH of 7.2 and available phosphorus and potassium are rated high. Soil density was measured from soil cores obtained in 1987 and is reported in Table 1. The density of the restored topsoil is equal to that of the undisturbed Clarion surface soil. The density of the surface 6-inch horizon where no topsoil was replaced is dense, about equal to the subsurface horizon of the undisturbed soil. Finally, the till substratum density in the research plots is greater than that reported for the undisturbed solum from 0 to 60 inches. Substratum densities in excess of 1.70 g/cc will greatly restrict root growth and water and air movement in the soil.

In the spring of 1979, a row crop rotation consisting of alternate years of corn and soybeans was initiated on the site. This is the common crop rotation used in the county. Adapted corn hybrids and soybean cultivars are selected each year and planted as timely as possible. Although the plots are tile drained, internal drainage is

slow and field work is usually delayed following heavy rainfall events by an additional 3-4 days compared to adjacent, undisturbed farmland. After the initial fertilization of all plots in the fall of 1978, the plots were fertilized only during the year that corn was grown until 1985. At that time, the plots that had received no topsoil were fertilized with 400 pounds of P_2O_5 per acre. Only N is applied to the corn plots at 150 pounds per acre each year throughout the study. The plots are chisel plowed each year except where a ridge till cropping system was installed in 1990. Both corn and soybeans are planted in rows spaced 30 inches apart.

RESULTS AND DISCUSSION

Crop yields have been greatly affected by weather conditions throughout the 13 years of research. Generally, wet field conditions have delayed field work and planting. Replanting has been required once. Precipitation and temperature data have been compiled from the official Webster City weather station located four miles northeast at the local radio station. These records are presented in Tables 2 and 3. The annual total precipitation for Hamilton County is 30 inches. During the study period, five years had below normal and eight years had above normal precipitation. The most severe drought occurred in 1988 when 18 inches of precipitation was recorded and temperature excesses were recorded as well.

The Clarion soil occurring on 2 to 5 percent slopes has a corn yield potential of 141 to 145 bushels per acre for uneroded and eroded phases, respectively. Soybean yield potentials are 46 and 45 bushels per acre for the same erosion classes. Surface soil thickness is generally 8 inches, subsurface thickness is 20 inches, and the substratum extends to a depth of 60 inches. Clarion soil with 2 to 5 percent slope is a prime farmland soil and constitutes 10 percent of the soils found in Hamilton County. Corn and soybean yield responses to topsoil thickness throughout the study are presented in Tables 4 and 5, respectively.

Although corn has been planted every year during this study, yields were not measured during three of those years (Table 4). Drought injury in 1982 and 1988 was very severe. Corn yields were considered insignificant, less that 5 bushels per acre. In 1990, corn planting was delayed until July 3 and the crop was frozen before it matured. Comparison of the research site with the reported county averages shows that corn grown with no topsoil and 6 and 12 inches of restored topsoil has yielded about 45, 60 and 62 bushels per acre, respectively. Over the thirteen year period, these yields are 33, 44 and 45% of the county average. In one year, 1987, the plots receiving topsoil yielded more corn than the county average for the year. Statistical analysis of the yield data shows a highly significant increase from the addition of topsoil but no significant difference between plots receiving 6 or 12 inches of topsoil.

Similarly, soybeans have been planted every year of the study (Table 5). Soybean yields are not reported for 1982, 1983 and 1988. During each of those years, drought injury was severe. Inspite of a July 4 planting date in 1990, the soybean crop reached maturity but yields were greatly reduced. Over the thirteen year

Table 1. Soil moist bulk density of restored soil treatments.

	Soil depth interval sampled, inches				
Restored soil, in	0-6	6-12	12-18	18-24	24-30
	g/cc				
No topsoil					
Average	1.732	1.899	1.874	1.926	1.929
Maximum	1.766	1.974	1.978	2.025	1.996
Minimum	1.693	1.827	1.811	1.850	1.827
6 inches					
Average	1.436	1.657	1.851	1.893	1.901
Maximum	1.562	1.787	1.891	1.941	1.981
Minimum	1.364	1.511	1.750	1.847	1.836
12 inches					
Average	1.412	1.505	1.840	1.929	1.974
Maximum	1.578	1.753	2.070	1.988	2.043
Minimum	1.249	1.329	1.568	1.886	1.921

Clarion (from Soil Survey)	Moist bulk density	Clay
Depth, in	g/cc	Pct
0 - 18	1.40 - 1.45	18 - 24
18 - 36	1.50 - 1.70	24 - 30
36 - 60	1.50 - 1.70	12 - 22

period, soybeans grown with no topsoil and 6 and 12 inches of restored topsoil have averaged about 10, 19 and 21 bushels per acre, respectively. These yields are 25, 46 and 52% of the county average. The yield response to restored topsoil compared to no topsoil is highly significant and the yield increase between 6 and 12 inches of restored topsoil is significant at 0.0205 (PR>F) value.

In 1990, a crop management variable was introduced at the research site. A ridged-till cultivator was used to build ridges upon which soybeans were planted in 1991. Adjacent to these plots were conventionally prepared flat seedbeds. Soybean yields were 28, 16 and 18% greater on ridged than flat seedbeds in no topsoil, 6-, and 12-inch topsoil treatments, respectively. This yield increase was highly significant at 0.0006 PR>F. The ridged tillage system can overcome some of the near-surface disadvantages. For instance, the ridge is better drained and consequently warms more rapidly in the spring. Even after heavy rainfall, the ridge is not submerged and consequently the soybean plants are not exposed to standing flood waters. One important observation in this study has been that the severity of Phytophthora root rot occurrence has lessened and more plants survive on ridged compared to flat seedbeds. The incidence of Phytophthora infection has always been greatest where no topsoil was restored. Although ridged topsoil plots resulted in greater soybean yields, the incidence of plant disease was less than in those plots with no topsoil.

Table 2. Growing season and annual precipitation and deviation from normal record for the Webster City weather station

Year	May		June		July		August		Annual
	Pcpt	Dev.	Pcpt	Dev.	Pcpt	Dev.	Pcpt	Dev.	Pcpt
	inches								
1979	3	-1	3	-2	6	2	9	6	37
1980	2	-2	4	-1	2	-2	6	2	21
1981	3	-1	7	2	3	-1	4	8	27
1982	8	3	3	-2	6	2	5	1	40
1983	5	1	4	0	8	3	4	0	42
1984	4	0	6	2	6	1	0	-4	35
1985	2	-1	3	-2	1	-3	8	-3	28
1986	4	0	5	1	5	1	3	-1	37
1987	2	-1	3	-1	8	4	6	2	33
1988	1	-2	1	-3	1	-3	3	-1	18
1989	2	-2	5	1	5	0	3	-2	27
1990	6	2	11	7	6	2	2	-2	36
1991	9	5	5	0	2	-2	4	0	42

Table 3. Growing season and annual temperature and deviation from normal record for the Webster City weather station

Year	May		June		July		August		Annual
	Temp	Dev.	Temp	Dev.	Temp	Dev.	Temp	Dev.	Temp
	degrees Fahrenheit								
1979	59	-1	69	0	72	-1	71	-1	45
1980	62	2	70	1	77	4	73	2	48
1981	58	-2	70	1	74	1	70	-2	49
1982	62	2	65	-4	74	1	70	-1	46
1983	56	-4	69	0	77	3	78	7	47
1984	57	-3	70	1	72	-2	73	2	47
1985	64	3	67	-3	72	-1	68	-3	46
1986	61	1	72	3	75	2	67	-4	48
1987	66	6	73	3	76	2	69	-2	51
1988	66	6	74	4	75	2	76	5	48
1989	59	-2	68	-2	74	0	70	-1	46
1990	57	-4	70	1	72	-2	71	0	49
1991	64	3	74	4	74	0	71	0	48

SUMMARY

The topsoil restoration research site at the northcentral Iowa location in Hamilton County is unique because topsoil was restored over substratum into plots cut to the depth to be restored. The substratum was not disturbed below the depth of the cut. Crop yields have varied from greater than the county average to complete failures. Soybean yields have achieved a greater percentage of the annual county average where topsoil was restored than corn. Where no topsoil was restored, corn has yield 33% of the county average yield compared to 25% for soybeans. Soybeans grown without topsoil have exhibited greater incidence of disease than corn.

Throughout the thirteen years of the study, the substratum has remained very dense. The substratum exposed in the surface 6-inch layer remains very dense even though this zone has been tilled every year. Consequently, soil management practices must be used that attempt to avoid the problems associated with dense soil. Recently initiated research using the ridged seedbed practice has overcome a portion of the drainage impediment at the site. Without spring tillage, planting can be carried out at the most opportune time; this lessens some of the risks of delayed planting with its loss of yield potential.

Table 4. Corn yield response to restored topsoil depth.

Year	Restored topsoil depth, inches 0	6	12	County average
	- - - - - - - - - - bushels/acre - - - - - - - - - -			
1979	75.7	136.4	124.8	140.6
1980	75.2	80.1	73.6	125.3
1981	106.0	113.5	126.2	141.1
1982				130.0
1983	18.3	13.7	17.0	104.0
1984	33.5	39.5	41.7	113.6
1985	40.3	31.2	23.5	140.1
1986	68.3	70.4	71.2	146.8
1987	66.1	148.7	156.6	140.9
1988				80.4
1989	58.0	91.3	99.4	154.4
1990				120.3
1991	41.3	57.4	65.7	123.5
Average	44.8	60.2	61.5	127.8
	- - - - - - percent of county yield - - - - - -			
1979	54	97	89	100
1980	60	64	59	100
1981	75	80	89	100
1982	0	0	0	100
1983	18	13	16	100
1984	29	35	37	100
1985	29	22	17	100
1986	47	48	48	100
1987	47	106	111	100
1988	0	0	0	100
1989	38	59	64	100
1990	0	0	0	100
1991	33	46	53	100
Average	33	44	45	100

Table 5. Soybean yield response to restored topsoil depth

Year	Restored topsoil depth, inches 0	6	12	County average
	- - - - - - - - - - bushels/acre - - - - - - - - - -			
1979	19.8	38.8	40.7	40.7
1980	15.3	31.9	29.1	40.1
1981	16.6	29.0	35.5	44.0
1982				37.1
1983				37.5
1984	7.7	14.0	17.0	34.1
1985	12.6	14.1	13.3	40.2
1986	12.5	30.7	34.1	41.5
1987	20.1	28.8	36.4	42.8
1988				24.4
1989	12.4	27.3	32.0	45.9
1990	4.0	12.0	15.8	39.1
1991	14.4	19.4	23.0	40.1
Average	10.4	18.9	21.3	39.0
	- - - - - - percent of county yield - - - - -			
1979	49	95	100	100
1980	38	80	73	100
1981	38	66	81	100
1982	0	0	0	100
1983	0	0	0	100
1984	23	41	50	100
1985	31	35	33	100
1986	30	74	82	100
1987	47	67	85	100
1988	0	0	0	100
1989	27	59	70	100
1990	10	31	40	100
1991	36	48	57	100
Average	25	46	52	100

Coal Mine Subsidence Mitigation: Effects on Soil and Crop Yields

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Abstract. Longwall coal mining in southern Illinois causes surface land subsidence which can adversely affect agricultural land by creating wet or ponded areas. While most subsided areas show little impact from subsidence, some areas experience total crop failure. Previous studies have found average corn yield reductions of 4.7 to 95%. Coal companies mitigate subsidence damaged cropland by cutting drainage ditches or grass waterways, adding fill material, recontouring the landscape, or a combination of these methods. The objective of this study was to test the effectiveness of mitigation in restoring grain yields to their pre-mined levels. Seventeen sites in Jefferson and Franklin counties, Illinois, were selected for study. The sites represent conventional mitigation techniques on the predominate soils in the area. Corn (Zea mays L.) and soybeans (Glycine max L.) were harvested in 1988, 1989, 1990, and 1991 from mitigated areas and compared to yields from nearby undisturbed areas. Average four year corn yields were significantly (α=0.05) lower than reference areas. There was no significant reduction in soybean yields averaged over the four years. Soil fertility, bulk density, strength, texture, and hydraulic conductivity were measured to identify factors which may be limiting crop yields at mitigated sites. Fill material at most mitigation sites had SiL to SiCL textures, massive structure, and traffic-induced compaction interfaces. Yield reductions at some sites indicate the need for additional mitigation. This research demonstrated that mitigation of subsidence damage can be successful.

INTRODUCTION

The underground coal mining industry of the Eastern Interior Coal Basin is moving towards high extraction mining methods. These methods extract a higher percentage of the coal than conventional room and pillar mining methods. A consequence of longwall mining is immediate surface land subsidence (Gray and Bruhn, 1984). Subsidence from longwall mining is predictable and damage to buildings and other civil structures can be prevented or moderated (DuMontelle et al., 1981). Subsidence effects on agriculture land have been documented in Illinois (Darmody et al., 1989, Guither, 1986, Guither et al., 1985, Guither and Neff, 1983), in the United Kingdom (Selman, 1986), and in Australia (Ham, 1987). These effects include soil erosion, disruption of surface drainage, wet or ponded areas, and reduction of crop yields.

Southern Illinois is characterized by nearly level to gently rolling topography, shallow water tables, and extensive areas of poorly drained, slowly permeable soils (Fehrenbacher et al., 1984). Land subsidence from underground longwall coal mining creates wet or ponded areas which disrupt farming practices, causes low seed germination, and reduces crop growth and grain yields. Darmody et al. (1989) found a 4.7% average reduction in overall corn yields on subsidence affected land in Jefferson, Franklin, and Williamson Counties, Illinois. In the same study, areas classified as moderately and severely affected by subsidence represented 2.3% and 5.3% of the land area and registered 42% and 95% corn yield reductions, respectively.

Coal companies repair or mitigate areas adversely affected by subsidence by cutting drainage ditches or grass waterways, adding fill, recontouring the landscape, or a combination of these methods. Drainage ditches are typically constructed using small tractor-pulled scraper pans. Fill material is either dug from existing ditches, borrowed in the construction of a pond, or taken from high spots in the field. In the last, topsoil is pushed aside using bulldozers or stockpiled using scrapers in both the borrow area and the area to be mitigated. Subsoil from the high spot is used as fill. Topsoil is then returned to both areas. Fill depths typically range from one-half to three feet. For this study mitigation techniques were classified into three types: (1) Ditch, (2) Fill, and (3) Ditch plus fill. The success of mitigation in restoring grain yields is dependant on a number of factors, including the amount and type of mitigation work necessary, the resources and materials available for the job, and the skill of the operators performing the work. Direct measurements

on the amount of subsidence or predicted amount of subsidence were not required by the Illinois State Department of Mines and Minerals when mining permits were issued in 1982 and 1983 (Dan Barkley, 1991, personal communication). Consequently, the amount of subsidence at individual research sites is unavailable. Nevertheless, it is intuitive that there may be a relationship between the amount of subsidence and mitigation success.

Cropland reclamation after underground mining is not well documented. However, there are numerous publications on reclamation of cropland after surface mining for coal. Soil compaction caused by large earthmoving equipment used in subsoil and topsoil replacement has been identified as a major factor limiting crop productivity (Fehrenbacher et al., 1982). While the equipment used in subsidence mitigation tends to be smaller, the potential for soil compaction from scrapers excavating and placing fill and from bulldozers used for cutting ditches still exists. Soil compaction causes an increase in soil density and a simultaneous reduction in fractional air volume (Gupta, et al., 1989). Consequently, plant growth is altered due to poor soil aeration, low nutrient and water availability, slow permeability, and mechanical impedance to root growth (Indorante et al., 1981). Fehrenbacher et al., (1982) found significant differences in corn yields and root densities between different soil replacement techniques. Their research demonstrates the importance of sound soil replacement.

The effectiveness of cropland mitigation after longwall mine subsidence on grain yields and soil physical properties has not been documented. The objectives of this research were to: (1) measure the effectiveness of mitigation in restoring corn and soybean yields to pre-mined levels, (2) compare soil physical properties on mitigated soils and nearby undisturbed soils to identify soil physical factors which may be limiting crop yields, and (3) identify effective or deleterious reclamation methods and make recommendations to improve future mitigation work.

MATERIALS AND METHODS

Seventeen sites were selected in Jefferson and Franklin Counties, Illinois, from an earlier study which identified subsidence-affected areas (Darmody et al., 1988). Crop yields and soil physical properties were not measured at all sites in all years due to logistic problems. The sites were in farmers' fields and received varying amounts of subsidence and mitigation. The dominant soil series were Okaw (Fine, montmorillonitic, mesic Typic Albaqualf), Bluford (Fine, montmorillonitic, mesic Aeric Ochraqualf), and Cisne (Fine, montmorillonitic, mesic Mollic Albaqualf). The soils were classified as highly, moderately, and somewhat sensitive to subsidence damage due to their natural drainage and landscape position (Darmody, et al., 1988). A site consisted of the mitigation area, usually no larger than one-half hectare (1.2 acres), paired with an undisturbed reference area within the same field. The fields were planted to corn or soybeans and managed by individual farmers. There was variability between sites in planting dates and other management practices, however, these variables were constant within a paired mitigated and reference site.

Four soil fertility samples were collected during harvest at mitigated and reference areas. A sample consists of a composite of 5 cores taken to a depth of 23 cm. Soil fertility levels were determined by a contract laboratory (Brookside Farms Lab. Asso., Inc. New Knoxville, Ohio 45871). Phosphorus and potassium levels were determined using a Mehlich 3 extractable procedure and inductively coupled plasma (ICP) spectrometry. Soil pH was determined by a 1:1 paste method and an electrode. Organic matter was estimated by a modified organic carbon combustion method at 350° C (Mark Flock, 1991, personal communication).

Corn and soybeans were hand harvested in the fall of 1988, 1989, 1990, and 1991. Yield estimates were based on the grain weight from sampling units of four 6.1 m long rows from mitigated and reference areas. Corn yields were corrected to 15% moisture and soybeans to 13% moisture. Since sites consisted of one mitigated and one reference area, true experimental error did not exist. A general linear model was used with the sums of squares partitioned out for site and treatment with the site by treatment within year interaction being used to test for treatment effects. The residual sums of squares reflect the sampling error for the experiment. A least significant difference (LSD) was calculated using the site by treatment within year interaction term as the error mean square.

Three undisturbed soil cores 7.62 cm in diameter were collected at mitigated and reference sites to a depth of 1.2 m using a Giddings hydraulic coring machine. The cores were divided into 22 cm segments from which a 7.62 cm long sample was taken from approximately the middle of the segment. The top two segments (0-22 and 23-44 cm) were discarded to avoid the plow layer and the E horizon. The samples were waxed into pre-cut PVC tubing to seal side walls and to keep the samples moist until analysis. Saturated hydraulic conductivity was determined by a standard constant head laboratory technique (Klute and Dirksen, 1986). After hydraulic conductivity determinations, the cores were placed in low pressure suction funnels and desorbed from saturation to field capacity. Bulk density by the core method (Blake and Hartge, 1986) and particle

size analysis by the hydrometer method (Gee and Bauder, 1986) were determined from the soil cores.

Soil strength was measured in situ to a depth of 110 cm using a constant rate cone penetrometer (Hooks and Jansen, 1986). Five samples were taken in mitigated and reference areas. A sample consisted of the mean of two replications. The 110 cm data profiles were separated into five 22-cm segments for statistical grouping. A mean penetrometer resistance value was calculated for segments three, four, and five. The means of paired segments were compared using an LSD (α=0.05) test. Segment one was discarded because of disturbance from annual cultivation and segment two was discarded because it coincides with the E horizon of the natural soil which was dryer than the same segment in fill.

RESULTS AND DISCUSSION

Soil Fertility

Soil test results for pH, organic matter, phosphorus, and potassium are presented in Table 1. Soil fertility could be adversely affected by subsidence mitigation in two ways. First, recontouring could expose less fertile subsoil and remove fertile topsoil. Second, fill material could be deficient in major or minor plant nutrients or organic matter, or could contain excessive amounts of sodium. Coal company reclamation supervisors report that topsoil is typically removed before adding fill and then replaced upon completion of the work. Organic matter estimates from fertility data confirm this for most sites. Since topsoil is mixed and replaced by reclamation activities, no differences in fertility levels are expected between reference and mitigated areas.

Phosphorus and potassium levels at some sites were lower than recommended for optimal yields for the soils studied (Illinois Agronomy Handbook, 1991). However, since soil fertility levels at mitigated areas were equal to or higher than nearby reference areas, differences in available phosphorus or potassium should not account for yield deficiencies in mitigated areas. Similarly, secondary nutrients analysis show no significant differences between reference and mitigated areas. Loss of applied nitrogen to corn crops due to saturated soil conditions in mitigated areas is a possible limiting factor. This factor was not tested, however, nitrogen deficiencies evaluated by visual inspection where not observed throughout the growing season.

Yield Response

Yields averaged over all sites for corn and soybeans are presented in Table 2. Average corn yields were significantly lower at mitigated areas in 1990 and 1991 and significantly lower when averaged over the four year study. Soybean yields were significantly higher in 1989 and significantly lower in 1991 but not statistically different averaged over the four years. During the drier growing season of 1988, crops in the mitigated areas appeared to have benefited from the extra water collected and held by subsidence troughs. In contrast, a wet spring in 1990 precluded planting or caused low seed germination in these same areas. Corn plant counts were significantly lower in 1990. Corn ear counts were significantly lower in 1990 and 1991, and significantly lower averaged over the four year study. Hence, both low plant stands and plant stress resulting in low ear counts account for lower yields in mitigated areas. The apparent better response of soybeans than corn to mitigation is attributed, in part, to a later planting date under typically better soil temperature and moisture conditions.

Crop yields at individual sites varied widely within a given year. As a consequence, "best case" extremes or sites where mitigated yield was higher relative to reference yields were usually not statistically different (Table 3). In contrast, most "worst case" extremes are significantly different. This indicates productivity has been returned to pre-mined levels at some sites, while at other sites significant yield reduction can still occur after mitigation. Table 4 shows crop yields for different mitigation methods. Ditch type mitigation showed statistically similar yields to reference yields. In contrast, adding fill or ditch plus fill mitigation was unsuc-

Table 1. Grand mean of soil test results.

Treatment	%O.M.	pH	P(lbs/a)	K(lbs/a)
Reference	2.4	7.0	57	198
Mitigated	2.6	6.8	59	216
Difference	+0.2	-0.2	+2	+18
Recommended§		6.0-6.5	50	260

§ Illinois Agronomy Handbook, 1991.

Table 2. Crop yields at subsidence mitigation research sites.

Crop	Treatment	1988	1989	1990	1991	Mean
		- - - - - - - - - -		bu/a	- - - - - - - - - -	
Corn	Reference	95	125	112	106	110
	Mitigated	96	116	79	74	89
	Difference	+1	-9	-33*	-32*	-21*
	LSD	7	17	15	24	12
	n§	6	7	11	4	28
Soybean	Reference	26	29	28	31	29
	Mitigated	25	36	24	25	27
	Difference	-1	+7*	-4	-6*	-2
	LSD	2	6	6	5	3
	n	7	3	3	10	23

* significantly different (α=0.05)

§ mean of n sites.

cessful in restoring pre-mined corn yields. Both ditch and fill mitigation were successful in restoring soybean yields to pre-mined levels whereas ditch plus fill was unsuccessful.

Soil Physical Condition

Soils at selected research sites were characterized to identify factors which may be limiting yields. Typically, mitigated sites were characterized by massive or platy soil structure in added fill material. Soil texture of fill and natural soil ranged from silt loam to silty clay. Fill material usually had less clay than the natural soil. Table 5 shows mean values for bulk density, penetrometer resistance, and laboratory saturated hydraulic conductivity. Low hydraulic conductivity values were observed in both mitigated and reference areas and are attributed in part to the medium to fine textured soil and fill material. Both reference and mitigated sites showed variability in hydraulic conductivity with depth. In mitigated areas, massive structure and compaction left by earthmoving equipment were observed in the soil cores, and contributed to low hydraulic conductivity. Also contributing to low hydraulic conductivity values in mitigated cores were inclusions of foreign material (i.e. wood, weeds) in the fill. In contrast, higher hydraulic conductivity values in reference soils are attributed to the natural moderately strong and strongly developed soil structure and to partially filled channels and voids left by crayfish and other soil fauna or plant roots. At many sites the hydraulic conductivity was only slightly different between reference and mitigated areas. All values are within the moderately low to moderately high Soil Conservation Service (SCS) conductivity class (U.S. Dep. Agriculture, 1991). Overall, there

Table 4. Overall yields for different mitigation methods.

Treatment	Corn	Soybean
	- - - - - - - bu/a	- - - - - - -
Reference	110 a§	29 a
Ditch	97 ab	28 a
Fill	76 b	29 a
Ditch+Fill	89 b	23 b

§ Means within columns followed by the same letter are not significantly different (0.05).

Table 3. Crop yield extremes at individual sites.

Crop	Year	Site	Reference	Mitigated	Difference
Corn			- - - - - - - - - - - - - - bu/a	- - - - - - - - - - - - -	
Worst case	1988	8	105	84	-21*
	1989	2	158	107	-51*
	1990	3	122	23	-99*
	1991	8	111	62	-49*
Best case	1988	6	84	116	+32*
	1989	13	74	91	+17
	1990	11	79	75	-4
	1991	1	111	109	-2
Soybean					
Worst case	1988	9	36	28	-8*
	1989	6	30	35	+5
	1990	14	32	15	-17*
	1991	15	37	20	-17*
Best case	1988	2	32	32	0
	1989	7	33	42	+9
	1990	8	33	36	+3
	1991	11	39	44	+5*

* significantly different (0.05)

Table 5. Soil parameters averaged over 45-100 cm depth

Mitigation Method	Bulk Density (g/cm^3)		Penetrometer Resistance(MPa)		Hydraulic Conduct.(cm/d)		n§
	REF*f*	MIT	REF	MIT	REF	MIT	
Ditch	-¶	-	1.6	2.3	3	7	1
Fill	1.48	1.41	2.0	2.3	21	18	4
Ditch+Fill	1.49	1.36	1.7#	1.9#	19	11	6

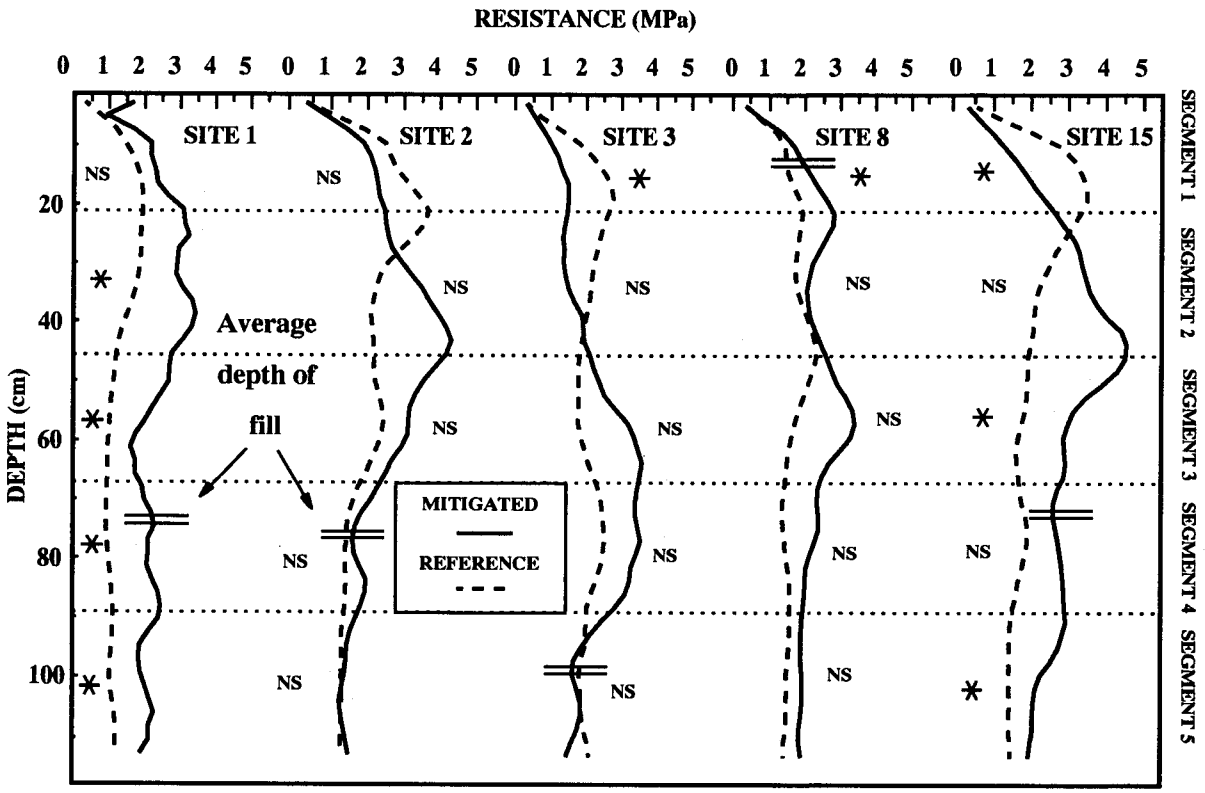
§ Mean of n sites with 9 determinations per site, *f* REF for Reference, MIT for Mitigated, ¶ No sample, # Mean of 4 sites.

appears to be little difference between mitigation method on hydraulic conductivity. In summary, soil hydraulic conductivity is often reduced as a result of mitigation, however, the change is not of great significance because of the moderately low permeability of the natural soil.

The lack of soil structure in fill material did not significantly change the bulk density from reference soils (Table 5). This is due in part to similar textures between mitigated and reference areas. Overall, mean bulk density values for both fill and ditch plus fill mitigation tend to be only slightly lower than reference soils. Hence, soil compaction as identified by higher bulk density does not appear to be affecting yield differences between mitigated and reference areas. It is possible that the sampling density was not great enough to detect changes in bulk density. Although the structure was massive in filled areas it was not necessarily highly compacted throughout. Compaction was mainly in traffic interfaces which may not have been sampled. Lower bulk densities were observed at sites which were reclaimed during dry conditions.

Penetrometer resistance measurements were taken in late spring when soil water content was approximately at field capacity. Soil compaction from reclamation was detected at sites 1, 2, 3, 8, and 15 (Figure 1). Prominent points (sites 2 and 15 at 45 cm) in the penetrometer profile identify traffic or scraper lift faces. These interfaces of high compaction disrupt internal drainage which may result in prolonged soil saturation. Mean values from selected soil depth segments were compared (LSD 0.05 level). Figure 1 shows that most mitigated and reference segment means were not statistically different. Site 1 is an exception, with higher soil strength below the depth of tillage. Root restricting soil strength values depend on soil texture, structure, moisture content, and method of measurement and therefore do not lend to direct comparison from other studies. Penetrometer resistance values in the range of 2 to 2.5 MPa have been identified as potential root restricting values (Taylor and Burnett, 1964). These values are exceeded at some sites and may be causing root restriction. However, in most cases the mitigated values are statistically indistinguishable from reference areas. Overall, penetrometer resistance is higher for all mitigation methods (Table 5).

Figure 1. Penetrometer resistance profiles of mitigated and reference areas. Mean of 10 determinations at each site.



*** significantly different (0.05 level)**
NS non-significant

SUMMARY AND CONCLUSIONS

Successful mitigation of land adversely affected by longwall mine subsidence in southern Illinois is dependent on adequate water drainage. Level topography and naturally poorly drained soils makes this task difficult. Results from four years of yield sampling show mitigation of subsidence-affected areas can be effective in restoring yields to pre-mined levels for soybeans but not for corn. In a previous coal mine subsidence study in southern Illinois, Darmody et al. (1989) found a 42% reduction in corn yields for areas moderately affected by land subsidence and a 95% reduction in yields for severely affected areas. This study found overall yield reductions of 19% for corn and 7% for soybean in mitigated areas (Table 2). This research showed that all types of mitigation (ditch, fill, and ditch plus fill) can be successful. Rainfall and other factors may compound yield response at any site to cause significant yield reductions regardless of mitigation method. Trends in this research relative to the number of sites studied suggest ditching is more successful than ditching plus fill or fill only. Site specific factors such as the amount of subsidence damage, and hence the amount of mitigation necessary, and field/landscape characteristics may bias ditching success rate. For example, ditching may be done when subsidence creates a gentle and continuous trough, as opposed to a localized depression or "pit" which would require fill. The disadvantage of ditch mitigation is that waterways in fields take land out of production and require maintenance.

Results from this study indicate only small overall changes in soil physical properties between mitigated and reference soils. Bulk density and saturated hydraulic conductivity were lower while penetrometer resistance was higher on mitigated areas. These small differences in soil properties are independently unlikely to affect crop yields. Field inspections revealed water drainage was inadequate for crop growth at some sites.

One must keep in mind that mitigated areas are very small in size and that a small decrease in yields on one-half hectare will not significantly reduce overall field yields. However, it is important that mitigation is attempted on all mine subsidence damaged agricultural land not only from a productivity standpoint, but also to prevent associated agricultural problems such as weed and pest control and to maintain normal field patterns for planting and harvest.

The results of this research indicate that the following practices may improve mitigation: 1) reduce soil compaction by working soil and adding fill when the soil is dry, 2) minimize traffic and use low ground pressure equipment on soil and fill, 3) apply deep tillage during and after mitigation work to alleviate compaction interfaces, 4) provide better water drainage by excavating existing drainage ways, and 5) add sufficient depths of fill to low areas. In addition, adding drainage tiles to mitigated areas may improve mitigation success. Drainage tiles are not commonly used in southern Illinois due to low soil permeability and siltation problems in high sodium soils. The Illinois Drainage Guide (1984) reports that a single subsurface drain with surface inlets may be more economical than surface ditches for depressions in these soils. In non-compacted fill material, a subsurface tile may provide adequate drainage for crop growth, provided an outlet is available.

As longwall coal mining in this region of productive agricultural soils increases, the need for effective reclamation is important to maintain the agricultural viability of the region.

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The Effects of Coal Mine Subsidence on Soil Macroporosity and Water Flow

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Abstract. Planned coal mine subsidence is increasing as more efficient methods of underground extraction are used. Unlike room and pillar mining, these methods extract most of the coal in a panel. Because no coal is left to support the roof, subsidence occurs over the mined out panel causing cracks to form in the soil.

A field study using Rhodamine B dye and bromide tracers was conducted to determine if subsidence fractures remain in the soil and contribute to increased preferential flow. The dye and Br^- solution was applied with 0.6 m of head to the soil. The soils were later sampled for Br^- and photographed to record dye distribution. Horizontal planes of the soils were excavated to expose the sampling surfaces. Image analysis was used to quantify the pre and post subsidence dye patterns.

Bromide distribution was inconclusive for predicting greater preferential flow after subsidence. However, dyed subsidence cracks were recognizable to 1.6 m depth in the soil above the mine panel edge. This zone is characterized by tensional forces in the soil which allows the cracks to remain open. Of all the trials, the solution at the panel edge site drained the fastest (less than 1 day, as compared to 4 to 7 days for the others). The mine panel center had no visible cracks remaining because the cracks closed completely due to compressional forces.

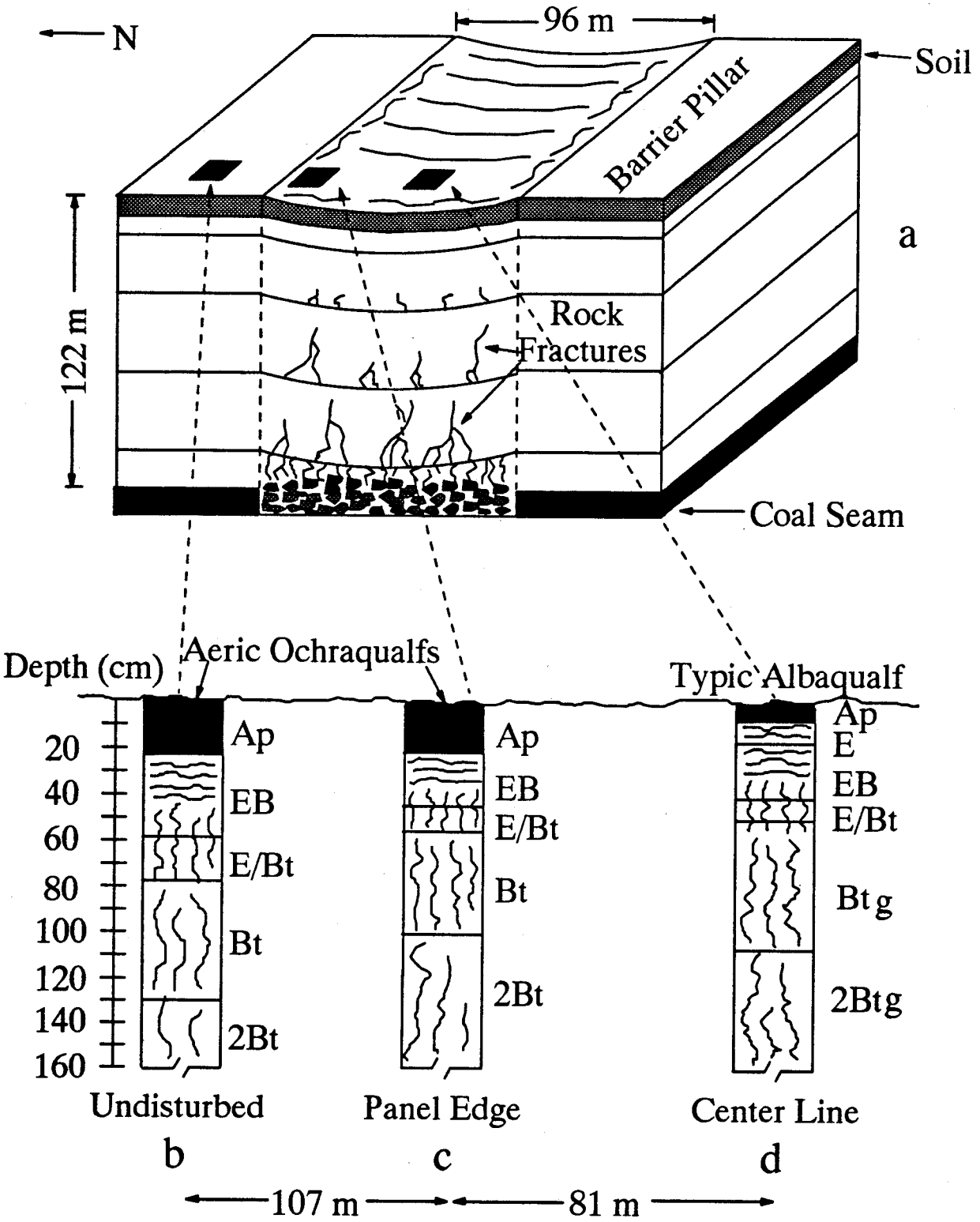
The results indicate that subsidence cracks remain in the soil along the mine panel edge eight months after subsidnece. Additionally, preferential flow was shown to be enhanced at this site following subsidence. However, evidence of this is lacking for the panel center. Further research is needed to determine if groundwater quality changes occur as a consequence of subsidence cracks along the mine panel edge.

INTRODUCTION

The coal mining industry in southern Illinois is adopting longwall (LW) mining as a new and more economical method of underground coal extraction (Darmody et al., 1989). Previous methods involving room and pillar mining left approximately 50% of the coal behind to support the overburden. Longwall mining recovers 100% of the coal in a panel and causes immediate subsidence of the overlying strata (Gray and Bruhn, 1984). Surface subsidence between 0.5 and 2.0 m is typical for Illinois and is dependent on the mining depth, height of the extracted coal seam, and the width of the mine panel (Bauer and Hunt, 1982) (Fig. 1). In LW mining all the coal is removed in panels as much as 200 m wide and 2000 m long resulting in immediate subsidence behind an advancing mining front. Besides the advantage of a higher coal extraction rate, this method of mining averts temporally and spatially random subsidence associated with room and pillar mining. This allows planning for mitigation of subsidence impacts. The elongate depression produced by subsidence is referred to as a "trough" (Bauer and Hunt, 1982). Soil cracks typically form at the trough edges. Although soil cracks up to 0.5 m wide have been observed, the majority are less than a few cm in width. The transverse cracks (Fig. 2) close as the dynamic subsidence wave passes. Longitudinal cracks, however, may remain open until surface processes close them (Van Roosendaal et al., 1992).

One goal of the project was to evaluate the potential of these subsidence cracks to enhance solute movement through the solum. Soils that exhibit strong preferential flow are said to have a biphasic flow regime that allows for rapid flow through larger pores while the water in fine pores remains relatively immobile (Sollins and Radulovich, 1988). As a consequence, fertilizers, pesticides, and other pollutants that are applied at the surface or which are not adsorbed within the soil matrix may be transported into the groundwater (Thomas and Phillips, 1979; Smith et al., 1985). Little information exists on the near surface alteration of water flow as affected by coal mine subsidence. The objective of this research was to measure the effects of coal mine induced subsidence on soil macroporosity and water flow.

Figure 1. Schematic showing subsided panel (a) and soil horizon designations and locations of; (b) undisturbed; (c) panel edge; and (d) center line plots.



MATERIALS AND METHODS

Site Description

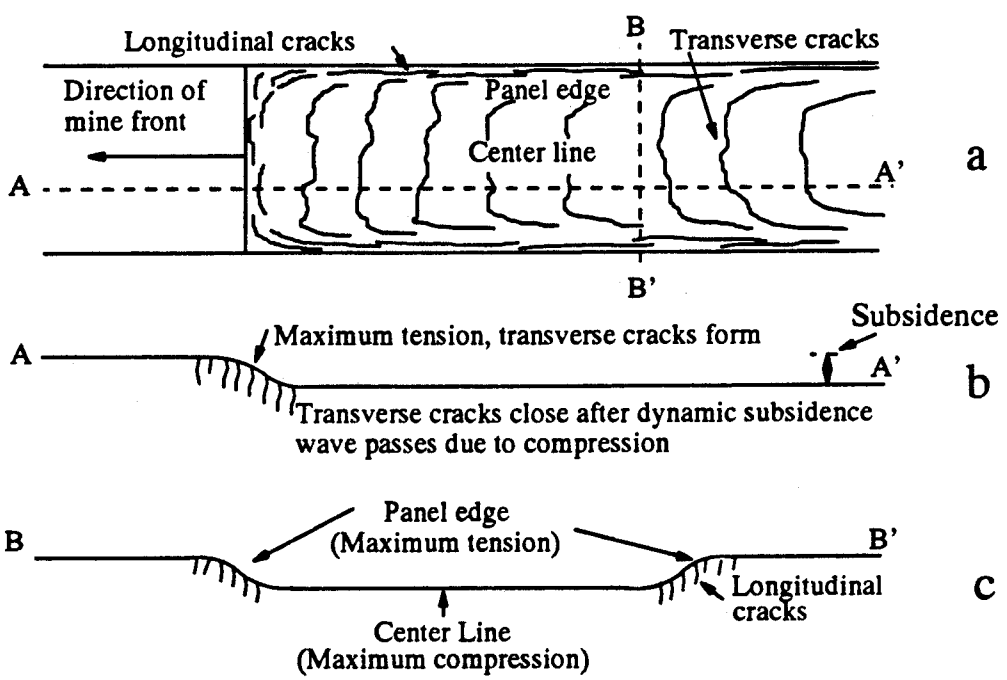
The study area is located in northwestern Saline County, Illinois on a gently rolling Illinoian age till plain. The soil developed under deciduous forest, however, currently it is used for row crop and small grain production. The Herrin Coal seam (1.8 m thick) that underlies the research site was mined at a depth of 122 m. Illinoian age glacial deposits approximately 8 m thick overlie Pennsylvanian age shales and argillaceous sandstones (Van Roosendaal et al., 1990). A loess mantle approximately 60 cm thick overlies the till (Fehrenbacher et al., 1984). The soil series at the study site were Bluford silty clay loam (fine, montmorillonitic, mesic Aeric Ochraqualf) and Wynoose silty clay loam (fine, montmorillonitic, mesic Typic Albaqualf) (Fehrenbacher et al., 1984). Both Bluford soils have a characteristic E/Bt horizon with bleached prism faces which overlies a weak fragipan. The Wynoose soil does not have as well expressed fragic characteristics.

Three pedons were selected to investigate the subsidence effects. Two of the pedons were located above the mine panel edge and center line (Fig. 1c and 1d). An undisturbed or control pedon was located slightly outside the subsidence affected zone (Fig. 1b).

Dye and Tracer Solution

The subsidence induced cracks were characterized using an absorbing dye and an anionic tracer. In August 1989 the three pedons received a solution of saturated Rhodamine B dye and KBr (0.5 g L^{-1}) with a solution head of 60 cm. The solutions were applied in 1.0 by 1.0 m bottomless tanks which were driven into the soil to a depth of 10 cm. Rhodamine B was used to show if subsidence cracks remain after their apparent closure at the soil surface. The dye has a strong visual contrast to the soil matrix and has been used successfully by others (Anderson and Bouma, 1973; Sollins and Radulovich, 1988). Bromide (0.5 g L^{-1} KBr) was used as a conservative tracer to compare water flow between pre and post subsidence (Germann et al., 1984; Onken et al., 1977). Subsidence occured in December of 1989. In August 1990 the procedure was repeated in adjacent pedons. Most of the Ap horizon was scraped off at each site before driving the tanks into the soil. This was done to prevent leakage of the solution outside the tanks into the friable Ap horizon, and to prevent excessive adsorption of the dye by organic matter. The tanks were carefully filled to avoid physically dispersing the exposed soil surface.

Figure 2. Schematic of a longwall mine panel: (a) overhead view of advancing mine face and cracks, (b) longitudinal side view, and (c) cross-sectional view.



Excavation and Sampling

One week after the dye application, the tanks were removed and trenches were dug on two sides to a depth of 3 m. The trenches facilitated excavation of horizontal planes below the tanks. Similar excavation schemes have been used by Logsden et al. (1990) and Ghodrati and Jury (1990). Incremental planes were exposed, smoothed with a scraper, and cleaned with a vacuum to remove debris. Photographs of each layer were taken of a centered 70 by 50 cm sampling area. After a layer was photographed, soil samples (2.5 cm diameter by 1.0 cm deep) of the sampling area were taken in a grid with 48 points for bromide determination. A grid was used to compare preferential movement of Br^- and dye (Seils, unpublished). Bromide was measured using an ion specific electrode (Owens et al., 1985). The lower detection limit was 2.6 mg $Br^- kg^{-1}$ soil. Both the soil and surface groundwater background Br^- concentrations were below the detection limit. Between 10 and 12 planes were sampled and photographed per plot to depths ranging between 130 to 180 cm. The depth of sampling on the pre-subsidence plots was determined by the absence of dye. However, during post subsidence sampling, lower depths were sampled to determine if Br^- had moved deeper in the profile than the dye. The distance between planes increased with depth as the variation in dye distribution decreased.

Characterizing Dye Distribution

Image analysis (JAVA video analysis software; Jandel Corporation, Corte Madera, CA) was used to quantify the dye patterns. Dyed areas of each plane were hand traced from projections of 35 mm color slides. This was necessary because a concise threshold between stained and nonstained soil could not be obtained from the original slides during image analysis. Dark clay and organic coatings, roots, iron/manganese concretions, etc., were not discriminated from dyed areas. A proper contrast was obtained with the hand tracings. Each plane was analyzed for percent dye area and number of dyed objects, and an apparent object size threshold of 0.03 cm^2 was obtained. Smaller dye stains may have been present but were not included in the image analysis.

Field Measurements

Three Uhland ring samples were collected from each horizon of the three study pedons (Uhland and O'Neal, 1951). Saturated hydraulic conductivity was determined using the constant head method (Klute and Dirksen, 1986). The samples were also used to measure bulk density (Blake and Hartge, 1986). Shear strength was measured with a hand held torvane sampler.

RESULTS AND DISCUSSION

Dye Movement

Dye patterns of all trials revealed greater preferential flow deeper in the profile (Fig. 3). Below the E/Bt horizon, flow was restricted to prism faces and larger macropores. This was observed during excavation, where the faces of larger aggregates were heavily stained whereas the interior contained little dye. The dye that did penetrate the interior of aggregates was due to flow via macropores which were easily observed.

The panel edge plot, Fig. 3b, shows easily recognizable dyed subsidence cracks. The panel edge (Fig. 1c) experiences tensional forces during subsidence due to the induced relief as the panel subsides (Van Roosendaal et al., 1992). Soil cracks which form along this zone occur at angles between 45 and 90 degrees relative to the advancing mining front (Fig. 2). The cracks are more clearly defined with depth, and extend well into the Bt horizon. As subsidence proceeds, a more significant fracturing occurs in these lower depths due to the greater bulk density, shear strength, and stronger consistence with depth (Table 1). These soil properties as well as the absence compressional forces prevent the cracks from closing. Immediately after subsidence fractures were observed at the surface along the panel edges. However, at the time of the solution application (eight months after subsidence) the surface fractures could not be seen. Near the surface, the cracks lose their distinctiveness after time because the soil is more friable, which allows for infilling of the fractures by natural processes.

In the post-subsidence experiment, the solution at the panel edge infiltrated in the shortest time (less than 1 day) as compared to the other plots (4 to 7 days). It is evident that the panel edge zone lacks sufficient compressional forces to completely close the fractures during the period of the study. Dye patterns of the center line (Fig. 3c) do not reveal cracks. Cracks that form along this zone form parallel to and behind the advancing mining front (Fig. 2). As the mining front advances beyond a given point in the center line, compressional forces are generated that tend to close the cracks. The lack of soil cracks along the center line may be due to either (1) the cracks closed completely due to compressional forces in this zone, or (2) the sample area did not include a subsidence crack. It is likely that the cracks closed completely due to compression. Surface cracks were found to be about 1 m apart at the panel edge. No cracks were observed at the center line during post subsidence excavation.

Figure 3. Dye patterns of pre- and post-subsidence trials.

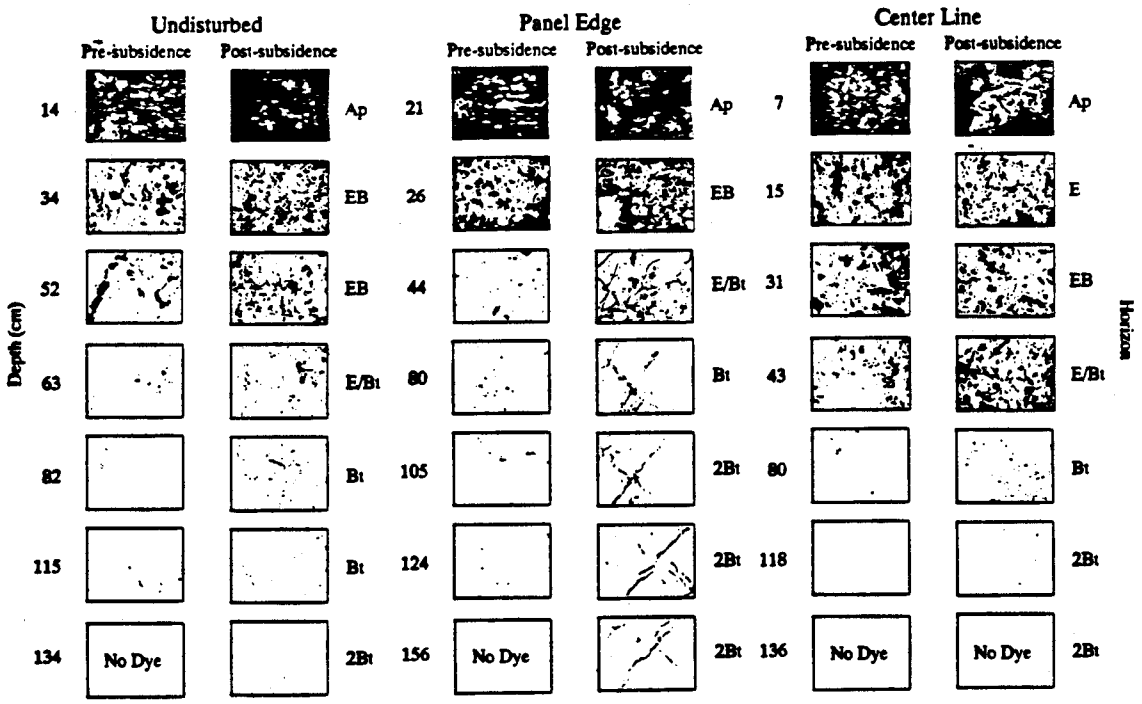
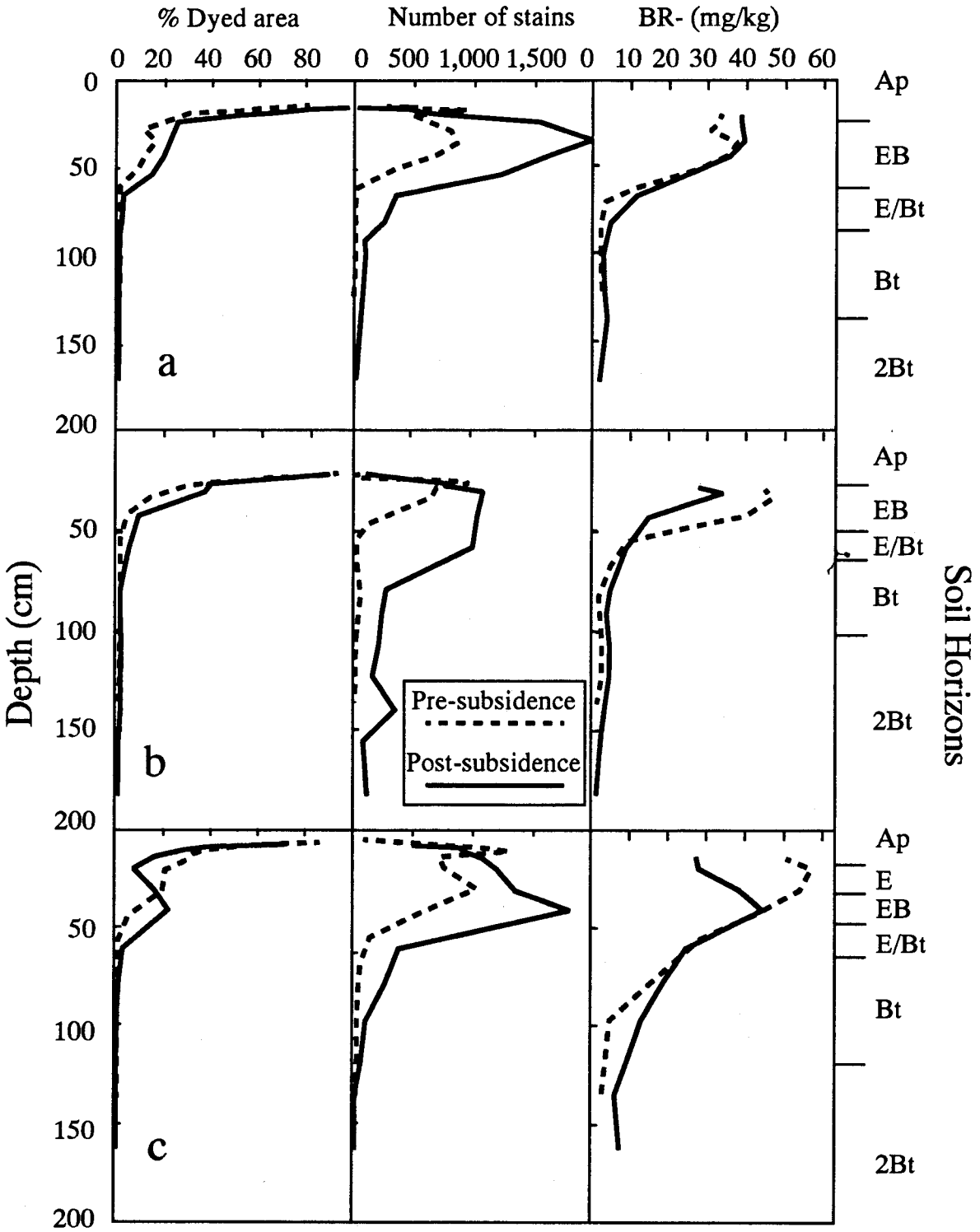


Table 1. Soil bulk density, shear strength, and consistence of the study plots.

Site	Horizon	Depth	Bulk Density	Shear Strength	Consistence
		(cm)	(g/cc)	(kg/cm^2)	
Undisturbed	Ap	0-24	1.50	0.41	Friable
	EB1	24-34	1.50	0.46	Friable
	EB2	34-50	1.46	0.41	Firm
	EB3	50-59	1.47	0.41	Firm
	E/Bt	59-78	1.57	0.67	Firm
	Bt1	78-107	1.53	0.60	Firm
	Bt2	107-130	1.58	0.65	Firm
	2Bt3	130-168	1.66	0.51	Firm
	2Bt4	168-186+	1.65	0.43	Friable
Panel Edge	Ap	0-21	1.47	0.31	Friable
	EB	21-43	1.53	0.31	Friable
	E/Bt	43-53	1.60	0.38	Firm
	Bt1	53-72	1.52	0.61	Firm
	Bt2	72-98	1.57	0.42	Firm
	2Bt3	98-122	1.56	0.42	Firm
	2Bt4	122-140	1.55	0.38	Firm
	2Bt5	140-195+	1.62	0.48	Friable
Center Line	Ap	0-8	1.26	0.39	Friable
	E	8-18	1.38	0.37	Friable
	EB1	18-27	1.44	0.38	Friable
	EB2	27-42	1.41	0.39	Friable
	E/Bt	42-51	1.53	0.37	Firm
	Bt1	51-91	1.47	0.56	Firm
	Bt2	91-108	1.49	0.56	Firm
	2Bt3	108-125	1.54	0.49	Firm
	2Bt4	125-176	1.65	0.61	Firm
	2Bt5	176-192+	1.64	0.56	Friable

Profiles of percent dye area, number of dye stains, and average Br^- concentrations with depth are presented in Fig. 4 for the three plots. All plots show an increase in the number of dye stains during post subsidence sampling. Since both the control plot and the subsided plots showed an increase in dye stain numbers, subsidence effects are not likely the cause of the increased number of stains above the panel edge and center line plots. Differences in soil conditions between pre and post subsidence likely contributed to the in-

Figure 4. Comparisons of % dyed area, number of dye stains, and bromide distributions among pre- and post-subsidence trials: (a) undisturbed, (b) panel edge, and (c) center line.



crease in dye stain numbers for all three plots. Fig. 5 shows profiles of percent soil moisture of the three plots for pre and post subsidence. All plots show greater moisture above the 110 cm depth during post subsidence. Greater soil moisture allowed the infiltrating dye to stay in suspension longer, which decreased the sorption of the dye on the soil particles. A result of this was a greater number of stained pores deeper in the profile.

All plots show little differences in the percent dye coverage (Fig. 4) between pre and post subsidence. Also, there is no discernable relationship between subsidence and increases in hydraulic conductivity of the panel edge and center line pedons as measured with the Uhland rings (Fig. 6). This is because the undisturbed plot showed dissimilar profiles of hydraulic conductivity for the pre and post subsidence trials which indicates

Figure 5. Percent soil moisture before and after subsidence at the time of the solution application.

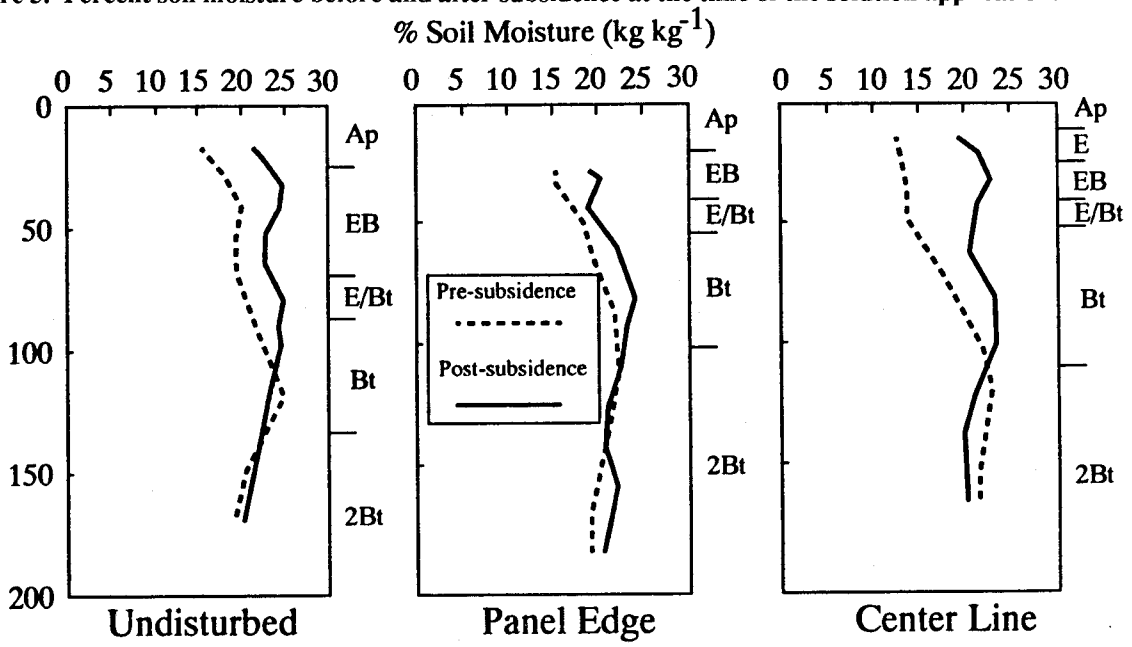
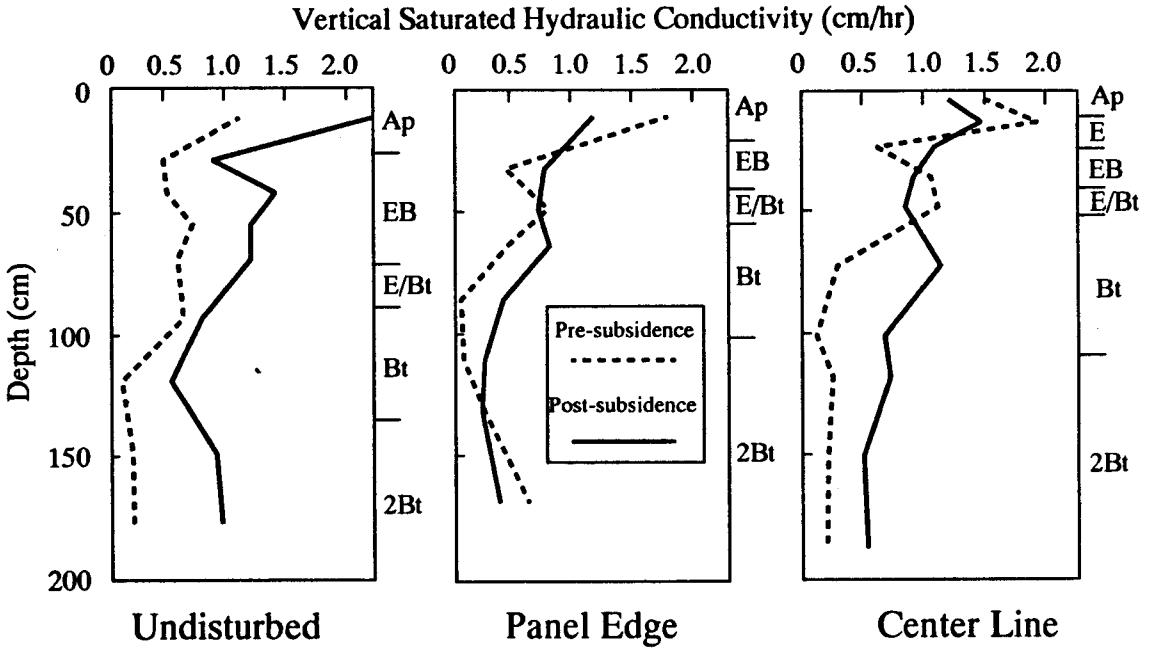


Figure 6. Vertical saturated hydraulic conductivity before and after subsidence. Average of three samples taken from the middle of horizons.



either (1) a high level of variability within the soil horizons; or (2) the method used for determining saturated hydraulic conductivity is unsuitable to detect differences in these soils. However, the fast rate of drainage of the solution tank along the panel edge indicates that an increase in hydraulic conductivity does occur on a larger spatial basis.

Evidence of little differences in dye coverage for the coal panel plots indicates subsidence did not increase total macroporosity throughout the whole soil matrix. Although the total flow paths were not significantly altered, subsidence cracks at the panel edge zone contribute to an increase in preferential flow, as evidence of the dyed cracks and the unusually fast rate of drainage of the solution. This increase in preferential flow along the panel edge could influence the movement of solutes through the solum. One concern is if subsidence occurs over a neglected landfill. The resulting soil fractures could facilitate the movement of contaminates to the groundwater.

The subsidence fractures contribution to bypass flow would be greater with increasing soil moisture (Hoogmoed and Bouma, 1980; Germann et al., 1984; Edwards et al., 1988). Also, soil fractures do not need to extend to the surface for flow to occur in them. Quisenberry and Phillips (1976) showed that preferential flow occurs below a tillage layer where macropores were disrupted. There was a stained large horizontal macropore directly above the E/Bt horizon (Fig. 3a). This indicates resistance to root penetration in this zone and water could flow lateral towards the fractures along active and decayed root channels.

Bromide Movement

Fig. 4 shows Br^- profiles for pre and post subsidence. Bromide values of each sampling depth are averages of 48 samples. All plots showed a steady decline in Br^- levels with depth. Statistical methods using the t-test and a 0.05 confidence level was used to compare Br^- concentrations between horizons of pre- and post-subsidence trails. Statistical analysis revealed that at lower depths, the control plot had significantly greater Br^- concentrations following subsidence. The upper horizons of the control plot had greater or equal concentrations. The panel edge plot had significantly lower levels of Br^- above the Bt horizon after subsidence. Below this depth Br^- levels were greater after subsidence. The center line plot showed similar trends as that of the panel edge plot. Because all plots showed greater Br^- levels after subsidence, a conclusive statement about the relation between transport and subsidence is not possible.

SUMMARY

A field study was undertaken to characterize soil cracks resulting from coal mine induced subsidence and to determine if greater preferential flow of water through soil occurs. A solution of Rhodamine B dye and KBr were applied to characterize changes in soil structure and water movement. Cracks remain in the soil at the mine panel edge eight months after subsidence as revealed by the dye. In addition, the dye solution at this site drained in a much shorter time, compared to the other sites. Dye patterns at the center line revealed no subsidence cracks. A control plot and the two mine panel plots all showed greater bromide concentrations and number of dye stains following subsidence which is believed to be a consequence of greater soil moisture at the time of application. Profiles of percent dye coverage with depth were similar for all plots between pre and post subsidence trails.

Both image analysis of dye stain patterns and the comparisons of Br^- profiles were inconclusive in predicting deeper water flow due to coal mine induced subsidence. However, visual observations and the dye drainage rate show that subsidence cracks along the panel edge zone may increase the possibility for increased preferential flow. This would be the result of flow through the subsidence cracks themselves, not due to changes in macroporosity of the overall soil matrix. The significance of increased preferential flow will depend on soil water conditions. Large scale investigations of surface groundwater quality changes beneath mined panels would aid in determining if subsidence cracks contribute to increased solute movement into the groundwater.

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