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SOIL DEVELOPMENT IN A COAL WASTE, SLAG AND SLUDGE ARTIFICIAL TOPSOIL MIX

by

Justine A. Cox, Rob J. Whelan & Stuart C. Thompson

Abstract. Waste disposal has become a major concern for industries that create a large amount of by-products due to the cost of landfill and environmental responsibility. Beneficial re-use of these by-products which contain resources for other industries, will solve some of these problems. An artificial soil mix has been created out of ironmaking and sewage wastes, for use in a revegetation program to improve the BHP Steelworks site in Australia. Coal washery refuse, blast furnace slag and sewage sludge have been combined to form a topsoil which is placed on waste mounds and revegetated. Field trials were established to evaluate the soil forming characteristics of this artificial media. The fine fraction (<2mm) of the particle size distribution decreased from 71% to 64% in one year, showing evidence of weathering and particle breakdown. Bulk density remained the same (1.0 g/cm^3) in a two year comparison. The pH of the soil mix declined from 7.6 to 7.1 in one year. Native tree growth in the soil mix was very good, although comparisons could not be made with real soil . The long term viability of the soil mix in relation to nutrient cycling could not be extrapolated with only two years of data. The potential is promising for the use of this soil substitute in urban landscaping, land restoration and revegetation, and opportunities for further research are available.

Introduction

Beneficial Waste Re-use

Industrial waste material has been typically dumped, used as landfill or otherwise disposed of and generally regarded as a problem, but there is an increasing shift towards the beneficial use of these by-products. Waste management strategies currently seek to minimise costs of disposal by the consideration of other methods of use besides dumping. Recycling by-product materials has helped improve the environment by reducing the amount going to landfill, but these methods still regard industrial by-products as wastes. The majority of by-products should be viewed as potential resources. Many 'waste' materials possess beneficial attributes for alternate industries or processes, which should then be fully utilised (see Joost *et al.* 1987, Logan & Harrison 1995). The physical and chemical characterisation of by-products enable these factors to be uncovered.

BHP (the Broken Hill Proprietary Company Limited) in Wollongong, on the east coast of Australia, has an integrated steelworks producing 5 million tonnes of steel a year. Along with this, approximately 2.5 million tonnes of solid wastes are produced, mainly coal washery refuse (CWR), blast furnace slag (BFS) and basic oxygen steel (BOS) slag. Some slag is re-used for sand, cement and road production,

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and coal wash has been used as structural fill in vast quantities in the local area (Thompson & Makin 1990). Waste emplacements of these by-products on site has occurred over many years with several off site locations also utilised. This has meant space for future material disposal has become increasingly scarce.

Revegetation of Waste Emplacements

Due to the urban location, environmental awareness and the company's decision to improve the conditions of the 800 ha BHP site, research into the revegetation of waste emplacements was initiated. Waste stabilisation and site rehabilitation methods of topsoiling and seeding with grass or cover crop were not undertaken. This was because the aim of the large scale project was to establish native vegetation in the waste material, and to eventually create a sustainable "urban forest" (Thompson & Makin 1990). There is no soil on site and very large areas are involved, so the cost and environmental impact of transporting native soil to the site was considered to be excessive. A soil substitute was required to provide the nutrients and growing conditions necessary for plant growth and survival. The abundance and availability of coal washery refuse and slag provided an opportunity to utilise waste products which contained elements beneficial for this purpose.

The BHP Soil Mix

While the major steelworks wastes provide an adequate physical structure for the basis of an artificial soil medium, there is a lack of organic matter, essential nutrients and micro-organism activity. Sewage sludge (biosolids) is a waste product of the sewage treatment system, and seems capable of providing these requirements. It is high in organic matter, contains organic nitrogen (which becomes available slowly), phosphorous and provides a suite of decomposer bacteria and fungi. An artificial growth medium has been created out of coal washery refuse, granulated blast furnace slag and sewage sludge in a ratio of 2:1:1. The materials are blended together with a front end loader to form a substitute topsoil, and stockpiled for various times, depending on the rate of utilisation. Several other wastes have been examined for growth potential, such as fly-ash, foundry sand and BOS slag and dust (Whelan *et al.* 1993) but are not used in the soil mix.

Constituents

The characterisation of this artificial growth medium can be estimated using soil analyses. However, as the material is man-made, unique and not a "real" soil it may be difficult to interpret some results. The properties of each component will also aid in understanding the soil's potential.

Coal washery refuse is the by-product of washing coal from underground mines in the local area for coke making. The majority of the shale and clay minerals are quartz and kaolinite. In addition, the material contains residual coal particles. The black waste is dewatered by belt press to 2-20 mm size fragments and is generally quite alkaline (Table I). The pyrite content is very low in this type of coal.

Blast furnace slag is the by-product of the iron-making process and is created at extremely high temperatures. It is granulated by a high pressure jet of water to a texture similar to coarse silica sand, and consists of calcium and aluminium silicates (especially wollastonite and mullite) (Thompson & Makin 1990). The size fraction is generally 0.2-2 mm and is also quite alkaline (Table I).

The sewage sludge obtained from several Wollongong sewage treatment plants is anaerobically digested after sedimentation (Table I). It's dewatered by either centrifuge or belt press. As well as contributing organic nutrients, there are also some heavy metals at low concentrations. The soil mix project uses all of the local area's sludge, and the volume of soil mix produced is constrained by this supply.

Table I. Physical and chemical characteristics of the constituents of the soil mix (from Whelan and Liangzhong 1991).

	particle size distribution (mm)	pH (H_2O) 1:1 w/v	Ec 1:5 w/v	N (%)
coal wash refuse	0.2 - 20	9.4	0.15	
blast furnace slag	0.2 - 2	9.2	0.21	
sewage sludge		6.4	6.19	5.24

Soil Mix Characteristics

The soil mix is a black, granular, relatively homogeneous mixture with an initially alkaline pH due to the slag and coal wash. The use of salt water to granulate the BFS has meant that some soils made in 1994 are reasonably sodic (Thompson & Makin 1990). Also, due to the granular nature of the mix, the water infiltration rate is very high. Given these attributes from the constituents analyses, no amelioration was attempted. Instead, native species tolerant of these factors were initially chosen. The plant response to this growing medium was exceptional. Many types of native trees, shrubs and ground covers grew quickly even though site conditions are often harsh. The adequate rainfall of the region (approx. 1000 mm/yr with a summer and winter maxima) could also contribute to this effect.

On-Site Revegetation of Waste Mounds

There are currently many types of revegetated areas around the industrial site, with more than 300,000 native plants growing in the artificial soil. A typical garden is comprised of a mound of waste coal washery refuse which ranges considerably in size, from small strips for car parks to boundary, screening mounds sometimes exceeding 1km in length. Soil mix is placed on top of the coal wash base (usually to a depth of 150mm), and bark chip type mulch added. Tree, shrub and ground cover seedlings from local nurseries are planted by hand and watered until established. Over the past eight years 20% of the steelworks site has been revegetated, using over one hundred Australian and exotic plant species growing in the soil mix. Detailed records and site history are kept for future reference. Weed control is carried out by mulching, using woodwaste or woven plastic matting, and herbicides. Lawn is grown in several areas where trees/shrubs are unacceptable (e.g. around heavy industry).

Soil Mix Development

The aim of the greening program was to create a self-sustaining forested ecosystem which required no maintenance, such as nutrient input, weed control or soil additives. It was also to create a value-added soil mix product from wastes for eventual use in the urban landscaping industry. Restoration of degraded sites, revegetation projects and other land rehabilitation efforts may also benefit from this type of media in the future. The long term aim of the soil mix project is for the artificial growing medium to function as a true soil whereby soil forming processes occur. Bradshaw (1987) recognised the importance of the soil substrate as the basis for successful revegetation and restoration attempts. Once physical, chemical and biological barriers to plant growth are ameliorated, there is

a much better (and quicker) chance for ecosystem development.

To create a self-sustaining ecosystem it is necessary once the plants (especially legumes) are established, for the litter layer to build up, decomposer organisms to be active and nutrient cycling to begin to operate. For the long term viability of the soil mix it is useful to assess the changes in the physical, chemical and biological characteristics over time which relate to soil development. Due to the nature of the material and the revegetation methods used, it is difficult to predict *a priori*, the rate and direction of these changes.

The factors that influence soil formation are: parent material, climate, slope (topography), organisms and time (Jenny 1941, Crocker 1952, Paton 1978). These universal forces would also act on the soil mix, changing its physical structure, chemical environment and biological activity with time. Many studies on the initial stages of soil development have identified important parameters of soil formation. These include particle weathering and horizon formation (Roberts *et al.* 1988), increases in nitrogen (especially), carbon, Cation Exchange Capacity and decreases in bulk density (Anderson 1977, Varela *et al.* 1993) and increased root biomass and microbial activity (Schafer *et al.* 1979). Revegetation of mine spoil with sewage sludge has shown that the organic source of nitrogen and phosphorous has dramatically improved the establishment of plants, due to the nutrients and the improvement in soil structure it provides (Topper & Sabey 1986, Seaker & Sopper 1988, Wong & Ho 1994).

The present study evaluates some physical, chemical and biological changes of the artificial soil mix in relation to soil formation over time. Several parameters were chosen to fully characterise the initial soil state and then to monitor the development of the mix in a field trial on a site at BHP Flat Products Division, Pt. Kembla for two years. Native tree/shrub species were used as indicator plants.

Methods

Field Trial Description

A very large coal washery refuse emplacement was the base of the trial site at the BHP Steelworks. This level area measuring approximately 60m x 20m, was situated on top of a hill overlooking a blast furnace. Twelve small plots (4m x 2m) were created for the control (no plants), oats and lucerne treatment (three replicates each) with four large plots (10m x 5m) created as the plots for native species. Each plot was lined with plastic sheeting to a depth of 1m of coal wash. The plastic surface sloped to direct leachate water into a sump of several 44 gallon drums welded together. Once backfilled and flattened, each coal wash surface was topsoiled with 300mm of BHP Soil Mix.

The four 'native' plots were planted with *Eucalyptus maculata* (Myrtaceae), *Acacia floribunda* (Mimosaceae) and *Callistemon salignus* (Myrtaceae). On each plot, fifteen individuals of each species were hand-planted (total 45). An irrigation system was established to water twice a week (sometimes three times in the first Summer), but this was stopped after the first year.

Soil Physical Parameters

Soil samples were taken approximately every three months for physical analysis. With a screw auger 20 cm long, ten random samples per plot were taken, and composited. Samples were spread thinly on newspaper then air dried for at least 48 hours. Pretreatment entailed light crushing to disperse the aggregates. Particle size distribution was measured by sieving the "soil" into fractions of: >16mm, 16-8, 8-4, 4-2, 2-1, 1-0.5, 0.5-0.25, 0.25-0.125, <0.125mm using a mechanical shaker. Not all samples were analysed, so only data collected over one year for the significant <2mm fraction is presented. Bulk density was determined at the end of the experiment for comparison with values examined by Whelan & Liangzhong (1991). This was

measured by the core method, where a known volume (29.5 cm^3) of soil was sampled, dried and weighed. Ten replicates were sampled from each plot.

Soil Chemical Parameters

Soil was sampled as before, with ten random auger samples composited and sub-sampled for individual analyses. Available nitrogen (nitrate/nitrite and ammonium) and total phosphorous concentration were measured three monthly for twelve months for all plots. The leachate water from each plot was also sampled after six and twelve months, for nitrate, ammonia and phosphate concentration. Each water sample was comprised of five aliquots from individual samples. The pH of the soil mix was measured at the beginning of the experiment and after one year. Ten replicate individual soil samples per plot were air dried, sieved and the <2mm fraction used in a 1:5 soil : $CaCl_2$ solution. Composite samples from the soil mix were also analysed for ten heavy metals (Pb, Cd, Zn, Cr, Cu, Ni, Mo, As, Hg and Se) at the beginning of the experiment.

Soil Biological Parameters

Native plant growth was monitored monthly for a year, then three monthly for another year. Tree height, and diameter of the stem at 20 cm above the ground were measured. This bioassay of the soil mix provides an integrated analysis of the physical structure (relating to rooting environment and water use), nutrient availability, potential toxicities and microbiological decomposer activity. Two pathogen indicators were also measured; enumeration of fecal coliforms and the presence of *Salmonella*.

Results

In the particle size analysis, the initial mean proportion of < 2mm fraction in the soil mix was 71% (± 0.7% SE) and had significantly declined to 64% (± 0.7%) over one year (Fig 1). This meant that the soil mix had

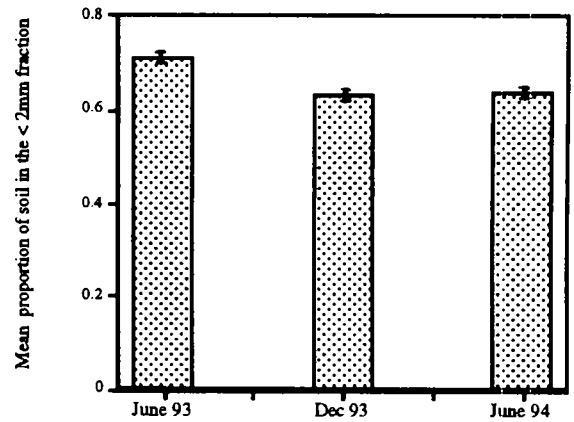

Figure 1. Mean proportion of soil in the <2mm fraction (after sieving) over one year. Standard error is shown.

undergone particle weathering and breakdown, and / or movement down the profile. This breakdown occurred quite rapidly after exposure to the environment, and the subsequent movement of particles has many consequences related to the leaching of ions into deeper layers. The bulk density of the soil mix initially was 1.0 g/cm^3, and after two years it had not changed with a mean value of 1.0 g/cm^3 (± 0.03).

The available nitrogen in the soil mix was initially high due to the sewage sludge, with a mean nitrate/nitrite content of 169 mg/kg (± 44) and ammonia of 50mg/kg (± 13). These values rapidly declined to a very low level in three months and remained there for another nine months (Fig 2). Total phosphorous concentration in the soil mix at the beginning of the experiment was variable with a mean of 740 mg/kg (± 115). Unfortunately there were some doubts about validity in all subsequent analyses, and so they are not reported. The nutrients in the leachate water were low. At six months, the mean nitrate concentration was 25.0 ug/ml (± 5.6), the phosphate

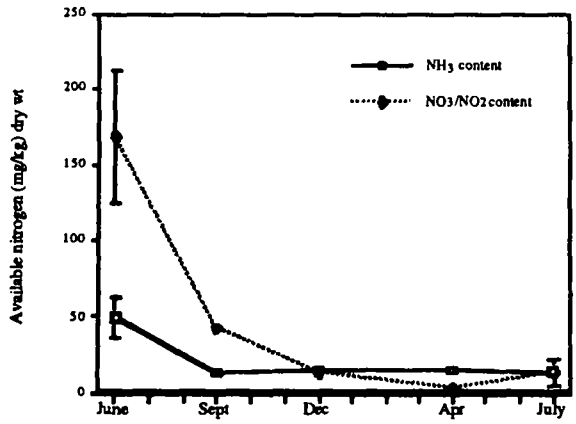

Figure 2. Mean available nitrogen (nitrate/nitrite and ammonia-N) content of the soil mix over one year (mg/kg dry weight).

concentration all <1mg/ml, and the ammonia concentration all <0.1 mg/L. After twelve months the mean nitrate concentration was a very low 0.95 mg/ml (± 0.23) with the phosphate and ammonia concentrations the same as before.

The initial mean pH ($CaCl_2$) of the soil material was 7.59 (± 0.04), and dropped to 7.10 (± 0.02) after one year. This meant that some acidification process had occurred. The heavy metal concentration of the soil mix are all quite low with mean values given in Table II. New draft guidelines on heavy metal concentrations of all biosolids products in Australia are presented for comparison (EPA 1995).

Plant growth was exceptionally good over the extent of the study duration. The native species grew rapidly after establishment and continued to develop. The *Eucalyptus* showed the most accelerated growth, and the *Acacia* also performed well (Fig 3). The *Callistemon* plants displayed relatively less growth which may be due to the advanced stages of the plants when the experiment began. Several plants of all three species died, with *Callistemon* most affected. Over the two years, weed invasion increased, but did not suppress native tree growth. This was mainly due to the delay in weed establishment, their annual life cycle and the large size of the trees when they eventually took hold. Insect attack was also noted. A number of *Acacia* plants flowered in the first spring, with most flowering in the second.

Table II. Heavy metal concentrations (mean and standard error) of the soil mix at the start of the field experiment (n=3), with the maximum metal concentration in any biosolids product from EPA Draft Environmental Management Guidelines (EPA 1995).

Heavy metal	Mean concentration in the initial soil mix (mg/kg)	Standard error	Max. conc. in unrestricted biosolids product (mg/kg)
Pb	4.77	0.19	150
Cd	1.30	0.06	3
Zn	31.0	1.20	200
Cr	7.60	0.50	100
Cu	24.67	2.33	100
Ni	5.50	0.21	60
Mo	2.77	0.32	-
As	0.22	0.12	20
Hg	0.99	0.13	1
Se	0.30	0.12	5

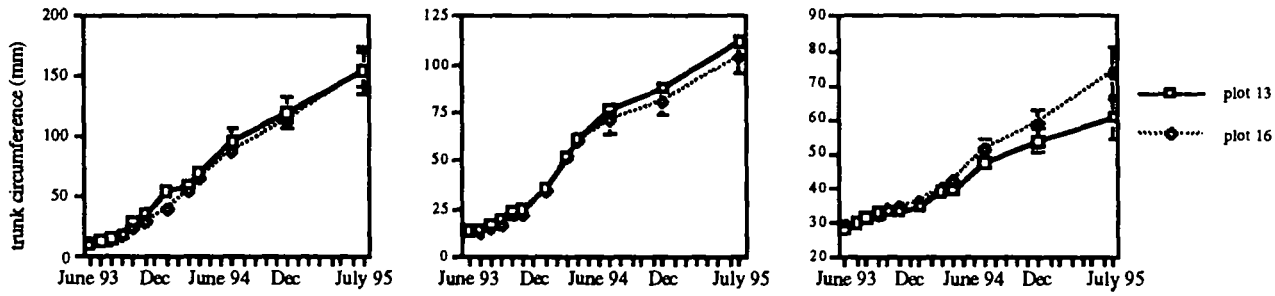

Figure 3. Native tree trunk circumference (mm) at 200mm above ground level for *Eucalyptus maculata*, *Acacia floribunda* and *Callistemon salignus*, over 2 years. Plot 13 and 16 are the 'native' plots.

There were never any *Salmonella* organisms detected in the soil mix in six months of monitoring. At the beginning of the experiment there was a mean of 220 CFU/g for fecal coliforms in the soil mix. After a month there were consistently <10 CFU/g, which remained at this level for six months. The new EPA guidelines for biosolids products have a limit of <1000 MPN per gram for fecal coliforms and no *Salmonella* sp detected in 50g, from a composite sample of five individual grab samples (EPA 1995)

Discussion

Physical soil development

The physical environment of the soil mix seems capable of supporting plant growth, by providing little restriction to root penetration, a range of particle sizes and adequate supply of available water. The results of this experiment suggest that weathering is occurring as there is a significant shift in the particle size distribution. The finer fraction of the soil mix has decreased over time which means that some larger particles have broken down to smaller components and moved down the profile. Coal washery refuse is the most likely component for this to occur as the clay minerals are readily broken down. Further weathering of the other components would also contribute to this increase. It was surprising to find the bulk density remaining the same after two years. An improvement in soil structure would have resulted from an increased value, as the loosely packed material becomes more aggregated. It is possible that the pozzolanic character of the soil mix has decreased with time which would counteract this trend. The sampling equipment may have influenced the accuracy, as the diameter of the corer was 20mm, and perhaps too small for this type of gravelly media.

Available nutrients

The nutrients available were provided by the conversion of the organic N and P source into readily available nitrate and phosphate. Plants did not show any signs of nutrient deficiencies, but clear indications of these have not been reported for the native species used. The initial flush of nitrate from the biosolids did not stay high for long. When the layer of soil mix was applied organic nutrients were exposed to oxygen and water. The aerobic organisms would be able to initiate their biochemical transformations under these optimal conditions (Alexander 1977).

The plants rapidly used the available nutrients, and any excess would have leached down the profile. As very little nitrate and virtually no phosphate or ammonia were detected in the leachate waters, we can assume that most of the available nutrients in the soil were used. This has great benefits, as the potential pollution problem from excess nutrients in the leachate may be minimised if there are enough plants to utilise the resource. The nitrogen cycle (transformations, additions and losses of N) of a community is of vital importance, and the establishment of one is often responsible for disturbed or degraded ecosystem recovery (Cundell 1977, Tate 1985, Sorensen & Fresquez 1991).

The pH of the soil mix decreased over one year which indicates that acidification processes had occurred. There are several ways in which this can happen, for example organic matter oxidation and leaching of carbonate materials. This has relevance to the increased availability of some metals to plants at lower pH values.

Plant growth

Plant growth and condition is a good indicator of soil fertility and potential toxicities. As the growth of the native species on this soil media was considered very good it was a positive sign for the short term success the soil mix. Of course these plants do not represent the vast range of conditions required for all growth, but observations in the established gardens on site suggest that limitations are not common. As the trees grew, shading / competition may have affected the growth rate of some trees, which would increase the variance within a plot. Insect attack may also have influenced relative growth rate. Several types of soil invertebrates were observed but not identified of quantified, these include springtails, Diplurans, Isopods, many ants and earthworms.

Comparisons of soil development

As there is no other artificial soil mix similar to this one, comparisons of rate and direction of change with other systems must be accomplished with caution. Some studies of soil genesis on mine spoil encounter similar conditions; for example, an initial homogeneous, gravelly mix, may be analogous. In these systems, in contrast to the artificial soil studied here, a lack of organic matter and nitrogen, severely limited plant establishment and development of a functioning ecosystem (Stroo & Jencks 1982, Sorensen & Fresquez 1991).

The revegetation attempts of coal mine spoil with sewage sludge in coal mining areas of the US, provides a more realistic comparison for soil formation. Joost *et al.* (1987) conducted a study on revegetation and minesoil development of coal waste, amended with sewage sludge and limestone. They found that after two years there was an improvement in soil structure, a reduction in bulk density and an increase in water holding capacity. Similar results may have occurred for the BHP soil mix had the same parameters been measured.

Another plant growth medium made of wastes, N-Viro Soil, is used in USA, Australia and England as a lime substitute, soil amendment and soil substitute. This material is composed out of dewatered sewage sludge and alkaline industrial by-products, such as lime kiln dust and cement kiln dust (Logan & Harrison 1995). There are many similarities with this media and the BHP soil mix, although the gravelly coal washery refuse would determine the difference in the water holding capacity, bulk density and other physical characteristics. The success of the N-Viro Soil in improving existing soil qualities over two years is recognised, and it would be interesting to determine the long term viability of the material.

Long term viability of the BHP soil mix can not be estimated by extrapolation from a two year study. A survey will be undertaken on site in the future of the many gardens that have been constructed in the last eight years. Many physical, chemical and

biological parameters will be measured to quantify trends in soil development over time. The biota of the soil system, i.e. plants, roots, microorganisms and invertebrates will be the focus of this study, due to their importance in nutrient cycling and ecosystem functioning in a new and developing native vegetation community.

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ACIDIC MINESPOIL RECLAMATION WITH AFBC BY-PRODUCT AND YARD-WASTE COMPOST[1]

by

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Abstract. Economic and environmental incentives to reduce solid waste volumes have spurred interest in the development of beneficial uses for urban and industrial by-products. This project investigated the reclamation efficacy and impacts on soil and water quality of two such materials: atmospheric fluidized bed combustion (AFBC) by-product and yard-waste compost. Six 1-acre watersheds were constructed on acidic abandoned mined land spoil (pH range 3.5 to 4.5). Two watersheds each were then reclaimed with 8 in of borrow soil, 125 tons/acre of AFBC, or 125 tons/acre of AFBC and 50 tons/acre of compost, and planted with a grass-legume seed mix. Watersheds were instrumented to record hydrographs of storm-water runoff events, measure erosion, and collect samples of surface- and percolate-water flow. One year after reclamation the AFBC and AFBC+compost treatments compared favorably with the traditional resoil reclamation practice. Spoil pH in the 0 to 4 in depth was increased to the range 6 to 8 which was similar to the resoil pH, and complete vegetative cover was successfully established on all watersheds. However, plant biomass production was approximately 2 times larger on the resoiled watersheds than on the amended spoil. Consequently, erosion was smallest on the resoiled watersheds. All three reclamation treatments increased runoff water pH to >7 and decreased soluble Al. Concentrations of Ca and S were larger in runoff- and percolate-water samples from AFBC-treated watersheds than from the resoiled watersheds. Trace element concentrations in all water samples remained very low and showed almost no treatment effects.

Additional Key Words: runoff, water quality, soil quality

Introduction

Conventional reclamation of abandoned mined lands (AML) involves placement of a layer of topsoil over the graded minespoil. Because topsoil was generally not conserved when AML sites were mined, soil must be "borrowed" from adjacent land thereby creating another disturbed area. The cost of reclamation becomes prohibitive if sufficient topsoil is not available adjacent to the minesite. The need for borrow soil could be reduced or eliminated by direct revegetation of acidic minespoil to which sufficient alkaline and organic amendments have been added. The use suitable of by-product or waste product materials for amendment of acidic minespoil would further reduce reclamation costs and also remove these materials from the solid waste stream.

The scrubbing of SO_2 from the stack gasses of coal-fired boilers (flue gas desulfurization, FGD) produces large quantities of FGD by-products, which in many cases are highly alkaline (Carlson and Adriano, 1993). The industries which produce FGD by-products (primarily electric utilities) have strong economic and environmental incentive to beneficially use FGD by-products. Although there is considerable variation among FGD by-products produced by various scrubber technologies, most consist of 3

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components; calcium sulfite/sulfate (gypsum), residual alkalinity (lime/limestone), and coal ash. Because of their alkalinity, FGD by-products can be used to neutralize acidity in soils (Stehouwer et al., 1995a, Marsh and Grove, 1992, Korcak, 1980) and minespoils (Stehouwer et al., 1995b). Because of its mobility, the gypsum component of FGD by-products may help to alleviate toxic conditions below the depth to which they are incorporated (Sumner et al., 1986; Farina and Channon, 1988; Alva and Sumner, 1990; Alva et al., 1990).

Atmospheric fluidized bed combustion (AFBC) is a type of FGD in which pulverized coal is combusted in the presence of lime or limestone sorbent. The SO_2 reaction product is anhydrite ($CaSO_4$) and is collected, together with unspent sorbent, in both the bed and fly ash streams.

Similarly, bans on landfilling of organic wastes, and legislative mandates to reduce solid waste volumes, have provided strong incentives for composting organic waste materials. Organic amendments, primarily sewage sludge, have been shown to significantly improve long-term minespoil revegetation success (Sopper, 1992). Composted organic wastes would likely provide similar benefits, and large volumes could be utilized in minespoil reclamation.

Large amounts of these materials were required (>100 tons AFBC $acre^{-1}$, >50 tons compost $acre^{-1}$) in order to improve spoil quality parameters such as pH, base status, pH buffering, microbial activity, and mineralizable C. However, these materials also contain large quantities of soluble salts and some trace elements of environmental concern. These could negatively impact soil and water quality both directly and through mobilization of trace elements in the spoil. Greenhouse experiments showed that when used at the appropriate rate, FGD by-products could ameliorate phytotoxic conditions in the spoil without adversely affecting plant growth (Stehouwer et al., 1995b, c). Analysis of greenhouse pot leachates also showed that at agronomically appropriate application rates trace element concentrations remained at very low levels. When used at lower rates, pH amelioration was insufficient resulting in poor plant growth. When applied at higher rates excessively high pH and soluble salts limited plant growth, and solubilization of organic C increased transport of trace elements.

This watershed-scale field study was initiated to compare conventional reclamation of an acidic minespoil by topsoiling, with direct revegetation of the spoil amended with an AFBC by-product alone and AFBC combined with yard-waste compost. The study was designed to investigate the revegetation success and the impacts on soil, plant, and water quality of the three reclamation practices.

Materials and Methods

In the summer and fall of 1994, during reclamation of an abandoned coal mine site located near New Philadelphia in east central Ohio, six 1-acre watersheds were constructed for the study described in this paper (Fig. 1). Exposed underclay material on the site was graded to a 4% slope and recompacted to serve as an aquitard. Thickness of the clay pad ranged from 10 to greater than 30 ft in an area 670 by 450 ft. A 5 ft wide by 1 ft high clay berm was constructed on the clay surface to hydrologically separate each 1-acre watershed. Following preparation of the clay aquitard, 4 ft of acidic minespoil material was placed over the recompacted clay and graded to a 4% slope. Each watershed was hydrologically separated by building a 10 ft wide by 2 ft high berm directly above the underlying clay berm. Berms were similarly constructed at the lower end of each watershed to direct surface water flow into a 10 ft long approach. Water flowed through an H-flume instrumented with a stilling well and a water stage recorder. Approximately 0.3% of total surface water flow was automatically diverted to a holding tank to allow sampling of each flow event. A trench was dug 5 ft up slope from the lower end of each watershed to allow the placement of a perforated 4 in tile line in a shallow trench (6 in deep) on the clay

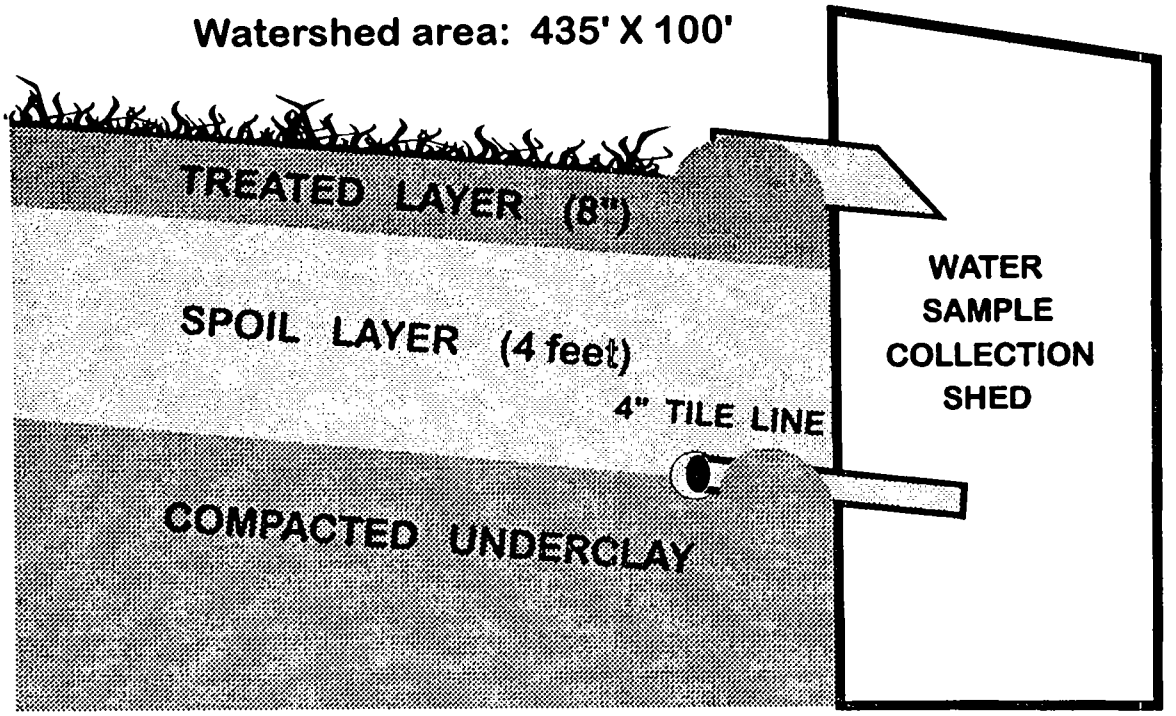

Fig. 1. Watershed design

surface. The tile line was covered with river-run gravel and the trench was backfilled. Any water which percolated through the spoil and flowed laterally over the clay was collected by the tile line and directed to an outlet pipe located below the surface water H-flume. All tile flow water was retained in a holding tank and sampled following each flow event.

Following completion of the construction phase, the three surface treatments listed below were applied to the spoil surface in each of 2 watersheds.

1. The conventional reclamation practice of application of 50 tons/acre of agricultural limestone on the spoil surface followed by placement of 8 in of borrowed topsoil material. Agricultural limestone was spread on the topsoil surface at a rate of 20 tons/acre and incorporated with a chisel plow and offset disc.
2. Application of 125 tons/acre of AFBC by-product followed by incorporation to a depth of approximately 8 in by multiple passes with a chisel plow and an offset disk.
3. Application of a mixture of AFBC by-product and yard waste compost applied at a rate of 125 tons/acre AFBC and 50 tons/acre compost followed by incorporation to a depth of approximately 8 in by multiple passes with a chisel plow and an offset disk.

Chemical characteristics of the minespoil and amendment materials are given in Table 1. The AFBC material used in this study was a blend of by-product collected from both the bed and fly ash streams. The by-product was conditioned with water at the power plant which resulted in the hydration of anhydrite to form gypsum, and of lime to form portlandite ($Ca(OH)_2$). The AFBC by-product had a neutralizing potential of 39% calcium carbonate equivalency. The source of the alkalinity in this material was predominantly $Ca(OH)_2$ with minor amounts of $CaCO_3$.

Watershed construction was completed in October, 1994 and plots were seeded to a grass-legume sward in

Table 1. Chemical characterization of minespoil, topsoil, yard-waste compost, and AFBC.

Parameter	Spoil	Topsoil	Compost	AFBC
Major Elements (%)				
Organic C	11.1	na	16.7	na
Total N	na	na	0.84	na
Aluminum	11.5	8.6	na	2.5
Calcium	0.04	0.07	1.69	26.1
Magnesium	0.50	0.53	0.35	3.65
Iron	5.57	3.96	1.77	5.9
Potassium	2.36	2.35	0.56	0.36
Phosphorus	0.07	0.04	0.15	0.03
Silicon	22.7	19.0	na	6.4
Sulfur	1.02	0.06	na	12.3
Trace Elements (μg g^{-1})				
Arsenic	46.3	5.5	11.47	71.5
Barium	701	503	na	204
Boron	na	na	39.11	418
Cadmium	0.8	3.3	<0.2	1.5
Chromium	94.4	95.6	284	42.2
Copper	26.8	62.8	69	49.5
Lead	78.0	15.9	26	17.4
Molybdenum	14.0	<0.2	27.79	22.4
Nickel	28.5	44.8	383	78.8
Selenium	4.5	<0.7	0.25	8.6
Sodium	150	150	207.9	1100
Zinc	<0.3	137.8	108	112
pH (1:1 water)	3.1	4.3	7.4	12.4

[2]Not analyzed.

November, 1994. The seeding mix included orchard grass (*Dactylis glomerata*), timothy (*Phleum pratense*), annual ryegrass (*Lolium multiflorum*), ladino clover (*Trifolium repense* Ladino), birdsfoot trefoil (*Lotus* sp.), and winter wheat (*Agropyron* sp.).

Baseline soil/spoil samples were collected in November, 1994 and again in June, 1995 by digging 3 cores (2 in diam) in each watershed. Cores were sampled in 2 in increments in the upper 12 in, and in 4 in increments from the 12 in depth down to the compacted clay layer. Soil samples were air-dried and ground to pass a 2-mm screen. Samples were analyzed for pH, electrical conductivity (EC), and for water soluble and Mehlich extractable concentrations of Al, Ag, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Se, Si, Sr, V, and Zn by ICP.

Water sample collection began in the spring of 1995. Following each surface-flow event a hydrograph was constructed for the event, sediments deposited in the approaches and H-flumes were removed, weighed and sampled, and 2-L water and suspended sediment samples were collected from the holding tanks. Water samples were analyzed for pH, EC, acidity and alkalinity before and after filtering through a 0.45μm membrane filter. Sediment concentration was determined

by drying and weighing the filter cake. Filtrates were analyzed by ICP for dissolved concentrations of the same elements as listed above. Total element concentrations of water samples were determined by digesting unfiltered samples in hot perchloric and nitric acid. Digests were analyzed by ICP for the same elements listed above. Tile flow water samples were collected after each flow event and analyzed as described for the surface water samples. Water samples were also collected and similarly analyzed from a sediment pond which collected surface-water flow from the entire reclamation site. Surface water samples collected before reclamation (before pond construction) were obtained from intermittent stream flow draining the site.

Plant biomass production was determined by cutting three strips (2.5 x 70 ft) across each watershed in August, 1995. Plant material from each strip was dried for 48 h at 60°C and weighed.

Results and Discussion

All three treatments resulted in profile surface pHs near or slightly above neutral (Fig. 2). With all three surface treatments, profile pH decreased with increasing depth. The pH of topsoil and AFBC+compost profiles decreased to the range 4 to 4.5. In the AFBC profile, however, pH was somewhat higher, in the range 5 to 6. The reasons for the higher pH with AFBC are not clear. Although the gypsum component of AFBC is expected to be more mobile than agricultural limestone (Sumner et al., 1986), downward transport of Ca^{2+} and SO_4^{2-} would not be expected to have such a large influence on pH. Furthermore, if the pH increase was due to the AFBC, the AFBC+compost treatment would be expected to show a similar pH response with depth. It remains to be seen if this pH difference persists in subsequent sampling.

Soluble salt concentrations in the surface layer of topsoil were much lower than in the AFBC- or AFBC+compost-amended minespoil (Fig.

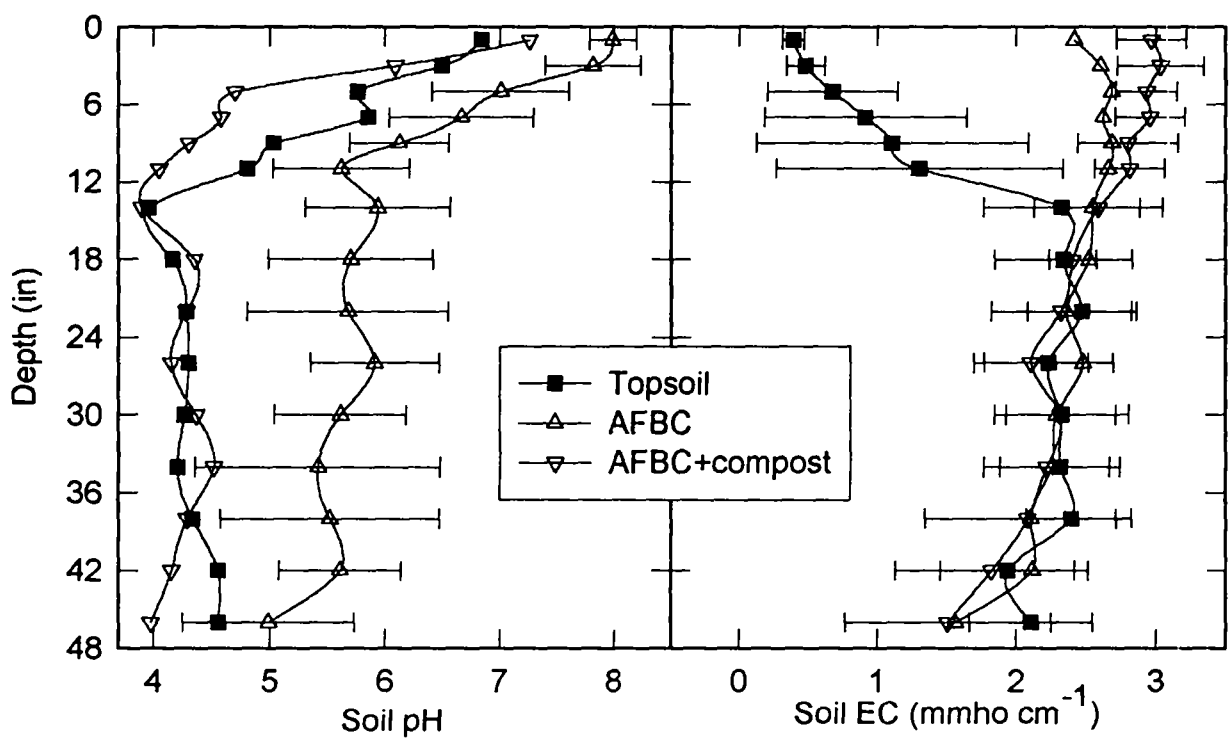

Fig. 2. Profile pH and electrical conductivity of acidic minespoil 9 mo after reclamation with topsoil, AFBC, or AFBC+compost surface treatments. (Error bars indicate plus and minus one standard deviation.)

2). Although AFBC alone did not increase spoil soluble salt concentrations, the addition of 50 tons acre^{-1} of yard-waste compost did increase salt concentrations slightly. Below the treated layers there were no differences among the three treatments with respect to soluble salts.

Establishment of vegetative cover was successful on all reclamation treatments, with 100% vegetative cover on almost all areas of all watersheds throughout the summer of 1995. Establishment was more rapid and growth was more vigorous on the topsoil treated watersheds. Topsoiled watersheds produced over twice as much plant biomass than did either the AFBC or the AFBC+compost treatments (Fig. 3). Although topsoil is clearly a better medium for plant growth than the minespoil material, amendment with AFBC did permit establishment of good vegetative cover on this otherwise toxic material. The high soluble salt concentration in the spoil material may account in large part for the less vigorous growth than on topsoil. It is expected that over time these salts will be leached downward. When this occurs, and if the spoil begins to develop other properties of a natural soil, plant growth may begin to approach that of the topsoil.

Prior to reclamation erosion rates from this abandoned mined land site were estimated at 420 tons acre^{-1} for a two-year storm. During the summer of 1995 no storm event produced greater than 2 tons acre^{-1} erosion from any watershed regardless of the surface reclamation practice. Thus both the conventional and the alternative reclamation practices were effective in greatly reducing erosion. However, both runoff volume (data not shown) and sediment losses (Fig. 4) tended to be smallest from topsoil watersheds and largest from the AFBC treated watersheds. Most of these differences appear to be directly related to the more vigorous vegetative growth on the topsoil watersheds.

All three reclamation treatments improved surface water quality. Prior

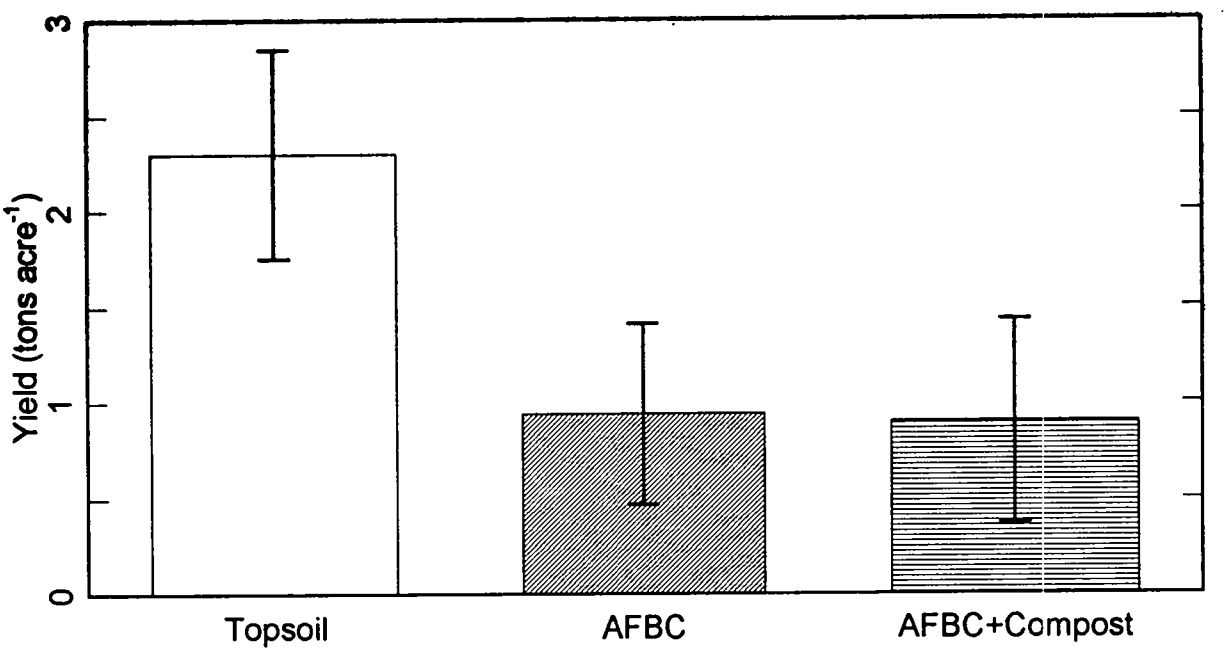

Fig. 3. Plant biomass yield in summer of 1995 on minespoil reclaimed with topsoil, AFBC, or AFBC+Compost. (Error bars indicate plus and minus one standard deviation.)

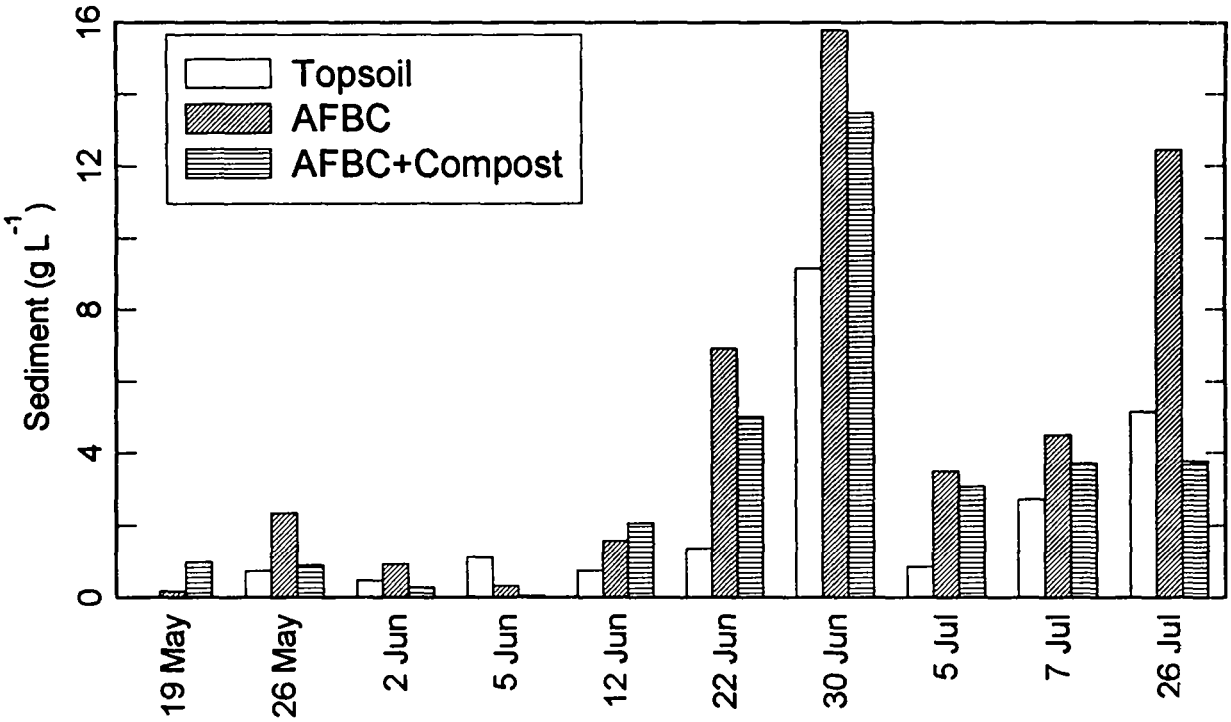

Fig. 4. Sediment concentration of 1995 summer storm runoff water from minespoil watersheds reclaimed with topsoil, AFBC, or AFBC+Compost.

to reclamation surface water pH was in the range of 2 to 3 with soluble Al concentrations as high as 120 mg L^{-1} (Figs. 5 and 6). All three reclamation treatments increased surface runoff water pH to the range 7 to 8, although the AFBC treatments tended to produce runoff water with slightly higher pH than did the topsoil. Changes in soluble Al showed just the opposite result. All three treatments decreased soluble Al to less than 0.3 mg L^{-1}. This result is expected given the increased pH and the low solubility of Al at near neutral pH.

Calcium concentrations in surface runoff water were clearly larger from the AFBC-treated watersheds than from the topsoiled watersheds (Fig. 7). This difference can be attributed to the much larger solubility of gypsum (a major component of AFBC) than limestone. As soluble gypsum is leached downward, and if vegetative cover becomes more vigorous, it is expected that the differences in soluble Ca between the AFBC and topsoil treatments will decrease. Similar results were observed with respect to soluble S (Fig. 8). Again the larger S concentrations with AFBC treatments can be attributed to the presence of relatively soluble gypsum in the AFBC. These differences are also expected to diminish gradually with time.

Several observations suggest that most of the water that reached the perforated tile line buried on the clay surface percolated through the spoil at the point where the trench was dug to install the tile rather than percolated through the spoil over the whole watershed area and flowed laterally over the clay surface. The spoil material was placed over the clay in several lifts using large earthmoving pans which resulted in significant compaction of the spoil. Surface runoff began very soon after the onset of a storm event and runoff volumes were large indicating there was little opportunity for percolation. Spoil core samples taken from just above the clay layer were quite dry even when the surface was wet. Finally, during surface flow

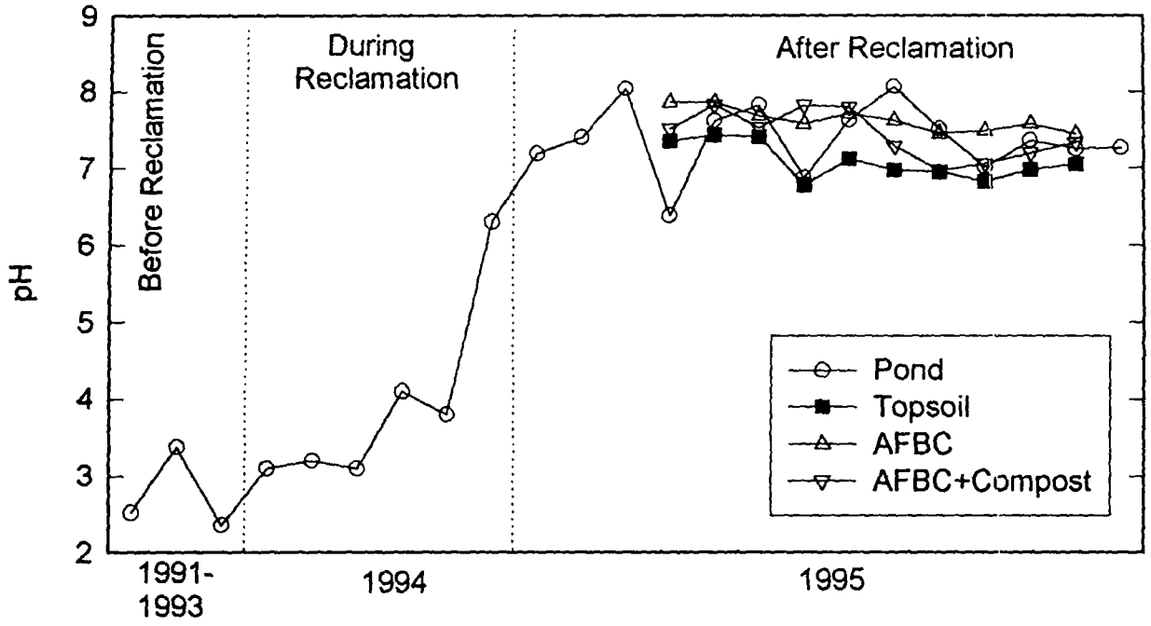

Fig. 5. pH of surface water runoff from minespoil reclaimed with topsoil, AFBC, and AFBC+Compost.

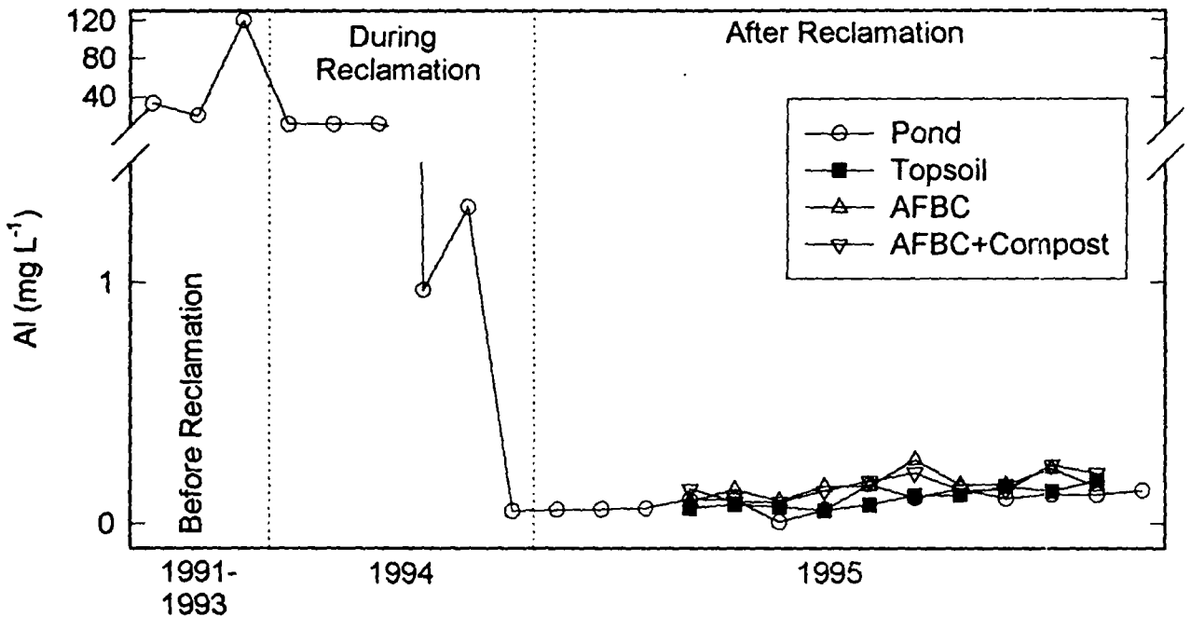

Fig. 6. Dissolved aluminum concentration in surface water runoff from minespoil reclaimed with topsoil, AFBC, and AFBC+compost.

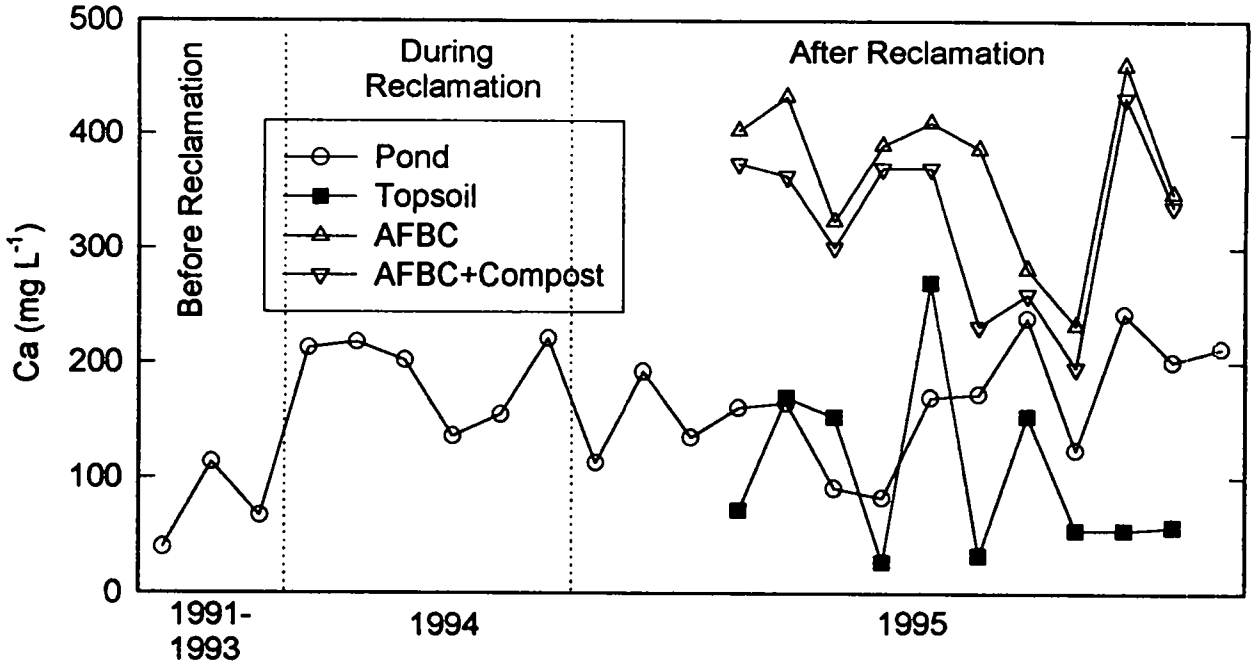

Fig. 7. Dissolved calcium concentration in surface water runoff from minespoil reclaimed with topsoil, AFBC, and AFBC+compost.

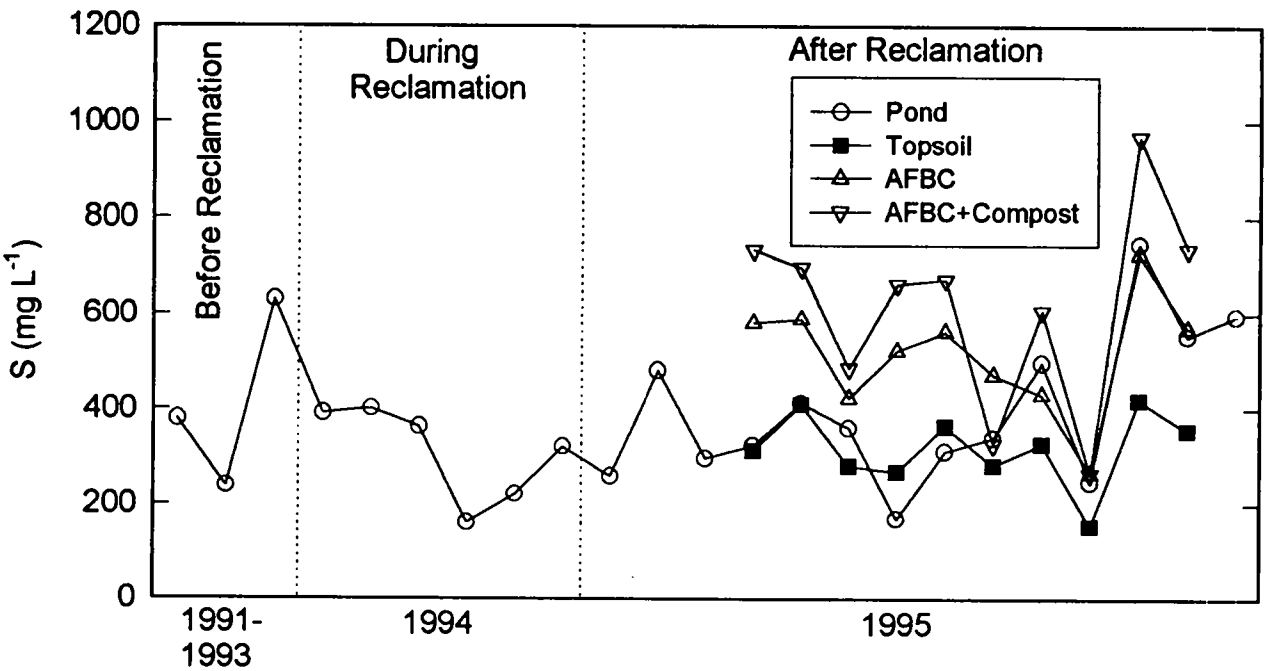

Fig. 8. Dissolved sulfur concentration in surface water runoff from minespoil reclaimed with topsoil, AFBC, and AFBC+Compost.

events water often puddled over the location of the trench. The tile water pH data also suggests limited interaction with subsurface acidic spoil and clay material (Fig. 9). Tile flow water from all three watersheds was only slightly lower than that of the surface water, and much higher than the pH of the subsurface spoil. Likewise soluble Al concentrations were in nearly the same range as that of the surface water (Fig. 10). Thus it appears that surface water is reaching the tile line via relatively rapid preferential flow paths and has limited interaction with the acidic spoil material.

The tile water is, however, interacting with the treated layers to a greater extent than the surface runoff water. Calcium concentrations in the tile water from all three watershed treatments were similar and in the range of 300 to 400 mg L^{-1} (Fig. 11). This was the same range as the surface water Ca for the AFBC treatments, but higher than for the topsoil treatment. Apparently the water percolating through the topsoil dissolved Ca from the ground agricultural limestone added to these watersheds. Reaction of the limestone with the acidic spoil released Ca^{2+} into the soil solution. Because of the large sulfate concentrations in the spoil (due to pyrite oxidation), the solubility of the Ca was controlled by gypsum, just as it was in the AFBC watersheds where gypsum was added.

For most of the summer, tile water S concentrations were larger in the AFBC watersheds than in the topsoil watersheds, reflecting the large addition of soluble sulfate in the gypsum component of the AFBC (Fig. 12). Toward the end of the summer, S concentrations from all three surface treatments and the pond appeared to be approaching a similar level. This may indicate that the system is approaching a new steady state condition where S concentrations are controlled by gypsum solubility.

Trace metal concentrations in surface water, tile water, and pond water generally remained very low and

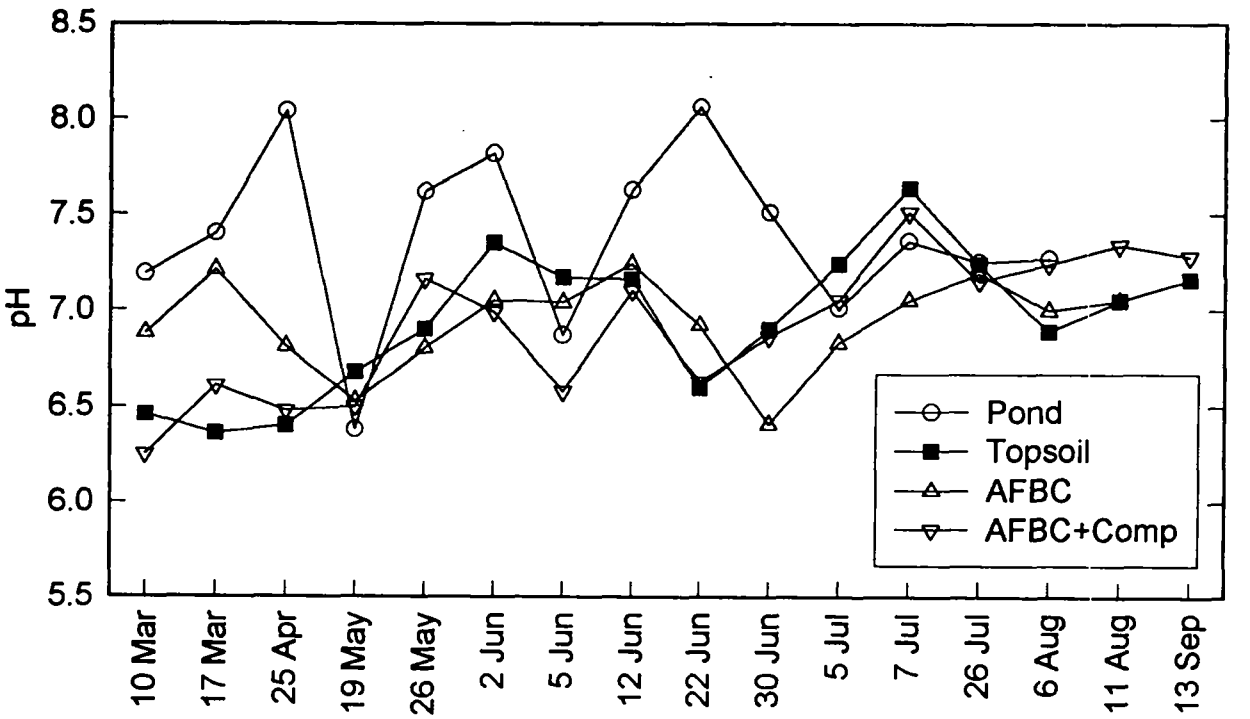

Fig. 9. pH of subsurface tile water flow from minespoil reclaimed topsoil, AFBC, and AFBC+compost.

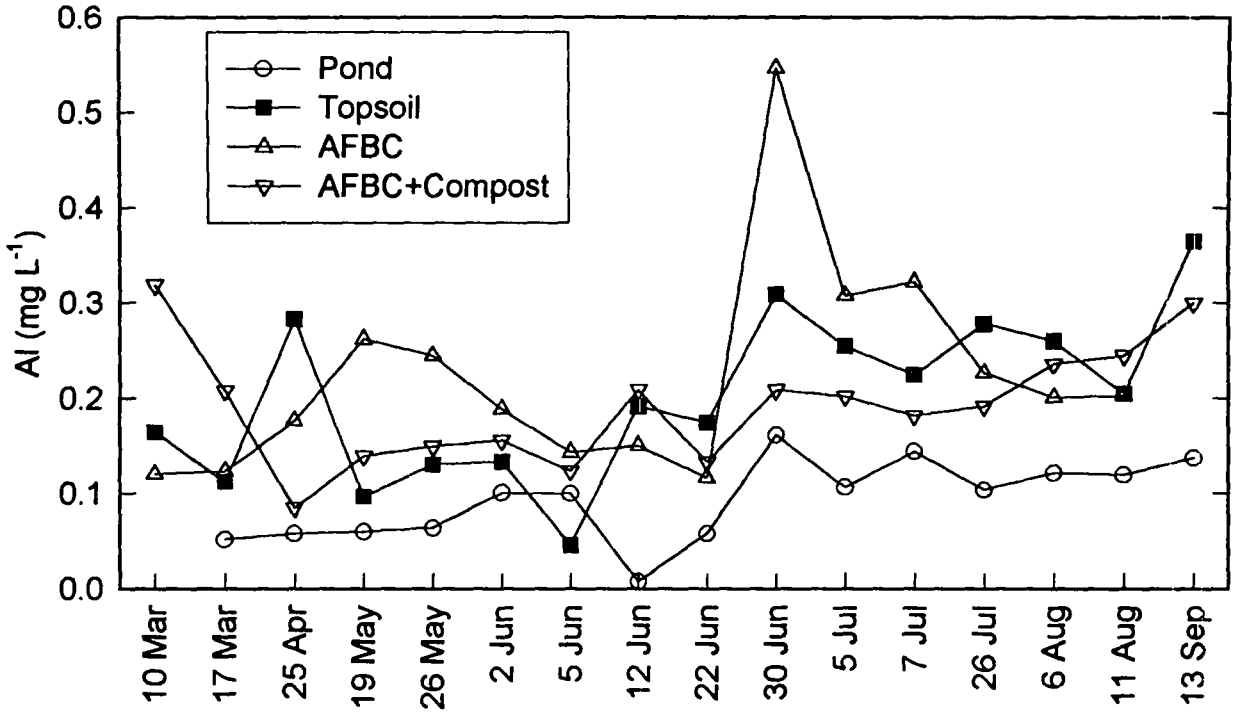

Fig. 10. Dissolved aluminum concentration in subsurface tile water flow from minespoil reclaimed with topsoil, AFBC, and AFBC+compost.

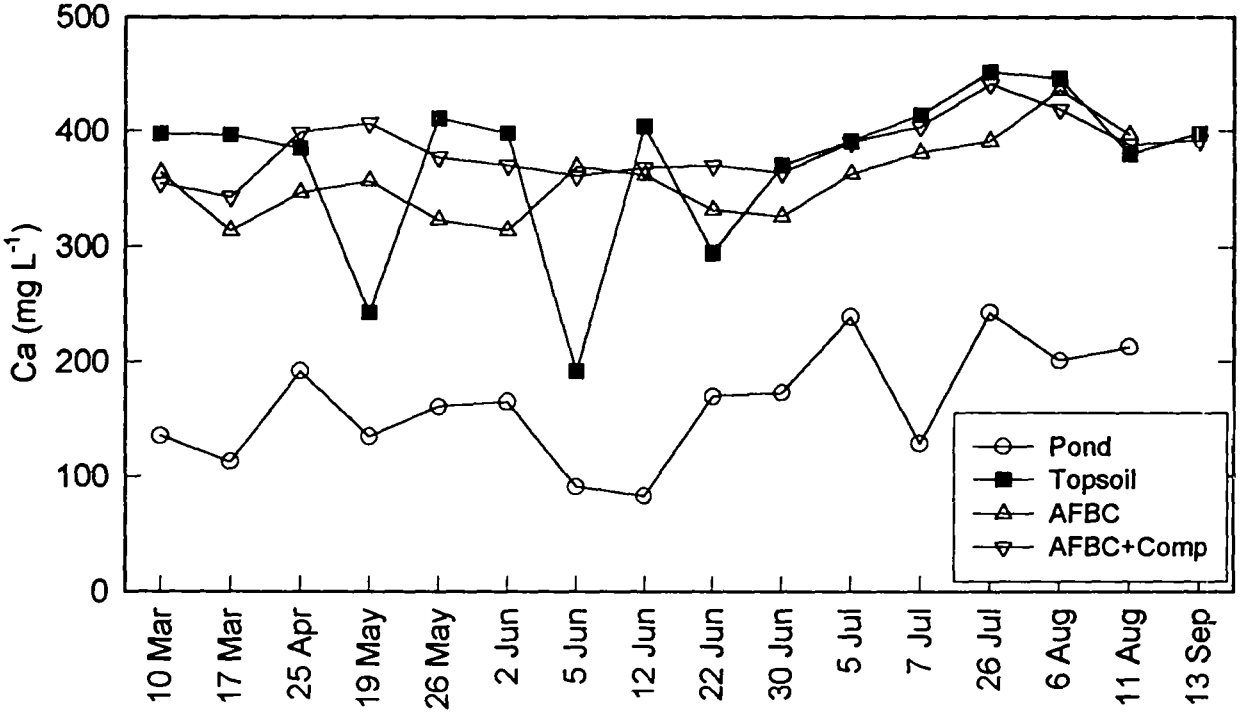

Fig. 11. Dissoved calcium concentration in subsurface tile water flow from minespoil reclaimed topsoil, AFBC, and AFBC+compost.

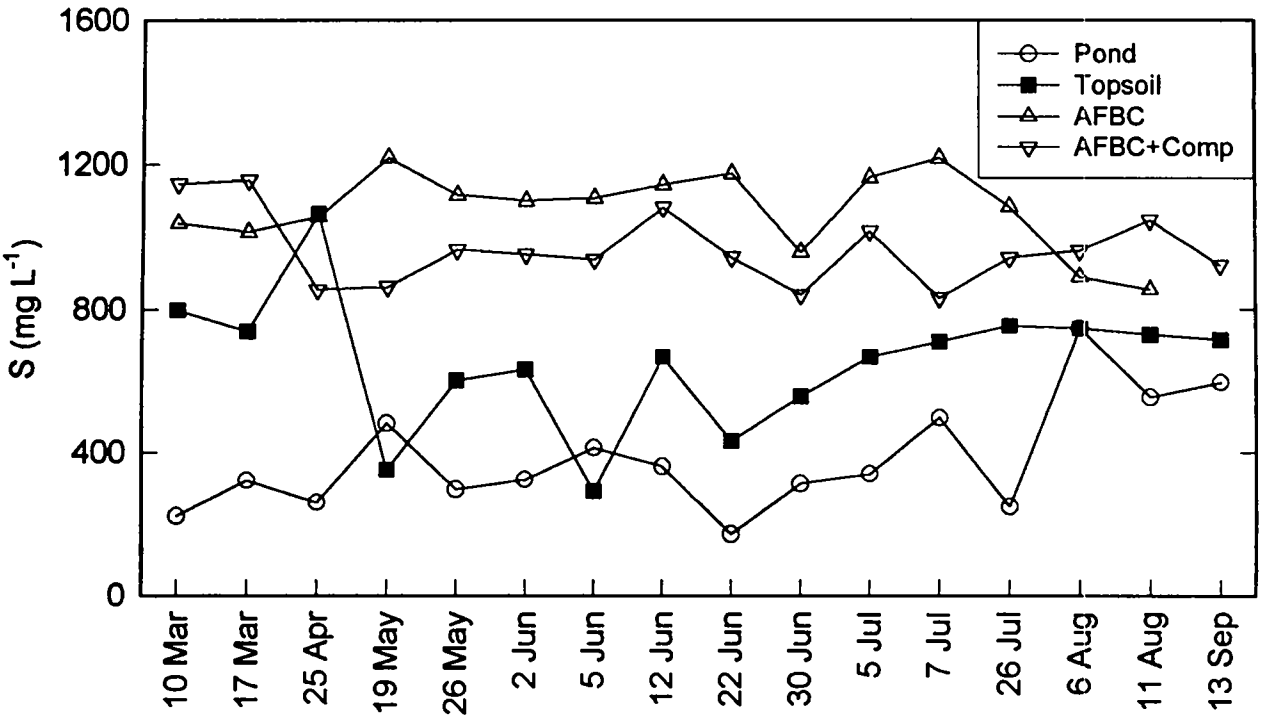

Fig. 12. Dissolved aluminum concentration in subsurface tile water flow from minespoil reclaimed with topsoil, AFBC, and AFBC+compost.

unaffected by the reclamation treatments (Table 2). Mean concentrations of As, Ba, Cd, Cr, Cu, and Se were below detection limits or below primary drinking water standards. Although occasional samples had higher concentrations of these regulated metals, these hits could not be ascribed to the AFBC or compost as all three reclamation practices gave values generally in the same range. This was generally the case for all measured trace elements. Mean Ni and Pb concentrations were above drinking water standards for the tile flow, but both mean and maximum concentrations were similar for all three reclamation treatments.

Boron and Mn concentrations both showed some response to the reclamation surface treatments (Table 2). These elements are of interest because of their potential for phytotoxicity at elevated concentrations. Boron was enriched in both surface and tile waters from the AFBC and AFBC+compost treated watersheds. This reflected the B added with the coal ash component of the AFBC by-product. It should be noted that B toxicity was not observed in the vegetation on these watersheds. Furthermore, the most phytotoxic B species are also highly water-soluble. Therefore the B enrichment indicated that the most phytotoxic B was being removed from the spoil rooting zone. Manganese concentrations in surface waters were similar for the three treatments, but in tile flow AFBC treatments had larger Mn concentrations than did the topsoil treatments. This indicated Mn was mobilized from the spoil in these watersheds. Mobilization of Mn following FBC by-product application has also been observed in acidic agricultural soil (Stehouwer et al., 1995a). The mechanism for this mobilization was not clear.

Conclusions

In the first year after reclamation, good vegetative growth on minespoil amended with AFBC or AFBC and yard-waste compost was achieved. Vegetative cover was nearly 100% over all areas of the 1-acre test

Table 2. Concentrations of trace elements in various water sources from minespoil reclaimed with topsoil, AFBC, and AFBC+compost. Values are means and maximum levels of all flow events in the spring and summer of 1995.

Element	Pond		Surface Runoff Water						Tile Flow Water					
			Topsoil		AFBC		AFBC+Compost		Topsoil		AFBC		AFBC+Compost	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
	mg kg^{-1}													
Ag	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
As	<0.04	0.083	<0.04	0.088	<0.04	0.096	<0.04	0.069	<0.04	0.106	<0.04	0.162	<0.04	0.095
B	0.526	1.082	0.147	1.867	3.163	6.875	1.977	3.681	0.207	0.961	2.945	5.178	1.644	3.279
Ba	0.023	0.040	0.017	0.032	0.012	0.020	0.010	0.017	0.017	0.032	0.017	0.024	0.019	0.042
Be	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	0.001	<0.001	0.002	<0.001	0.001
Cd	<0.001	0.001	<0.001	0.001	<0.001	0.001	<0.001	0.002	<0.001	0.010	0.001	0.011	<0.001	0.004
Co	0.008	0.024	0.008	0.025	0.010	0.034	0.014	0.036	0.223	1.216	0.416	2.258	0.341	1.266
Cr	0.003	0.009	0.003	0.010	0.005	0.012	0.005	0.011	0.009	0.019	0.010	0.031	0.010	0.019
Cu	0.009	0.023	0.010	0.030	0.006	0.029	0.013	0.027	0.005	0.048	0.002	0.022	0.006	0.035
Mn	1.33	3.527	1.63	7.330	1.06	3.722	2.68	8.042	23.94	124.7	32.80	198.4	34.27	122.4
Mo	<0.011	0.030	<0.011	0.020	0.028	0.065	0.018	0.043	<0.011	0.017	<0.011	0.033	<0.011	0.018
Ni	0.023	0.053	0.014	0.075	0.015	0.101	0.035	0.091	0.738	2.935	1.195	4.246	0.940	2.986
Pb	<0.02	0.048	<0.02	0.055	<0.02	0.050	<0.02	0.055	0.026	0.087	0.027	0.105	0.023	0.050
Se	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	0.100	<0.09	<0.09	<0.09	<0.09
Zn	0.065	0.144	0.065	0.135	0.021	0.139	0.002	0.113	0.139	0.192	0.382	0.204	0.131	0.217

watersheds. The establishment of vegetative cover directly on amended minespoil reduced erosion rates to less than 2 tons acre^{-1} for a 2-year storm. Although vegetative growth was more vigorous, biomass production was greater, and erosion was less on topsoiled watersheds than on watersheds with direct revegetation of minespoil, it is expected that these differences will become less as the spoil material begins to develop more soil-like properties. The successful revegetation of the minespoil can be attributed to increased pH and decreased concentrations of soluble Al and Fe in the minespoil. The less vigorous plant growth in the minespoil may be attributed in part to the large soluble salt concentrations in the spoil. It is expected that these concentrations will decrease over time as salts are leached from the profile surface.

No detrimental environmental effects were observed or measured as a result of using AFBC or compost in reclamation of acidic minespoil. Similar improvements in surface runoff and tile flow water quality were observed with topsoil, AFBC, or AFBC+compost. All three reclamation practices increased water pH to neutral levels and greatly decreased soluble Al. Concentrations of trace elements of environmental concern remained at very low concentrations in waters from all three reclamation practices. In those cases where measurable concentrations were present, there were no differences among the three reclamation treatments.

Results during the first year following reclamation show that the use of AFBC or AFBC and yard-waste compost will allow successful direct revegetation of acidic minespoil without adverse environmental effects. This site will continue to be monitored for several years to determine the long-term revegetation success and environmental impact of direct reclamation of minespoil with AFBC and yard-waste compost amendments.

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MUNICIPAL SEWAGE SLUDGE AND PHOSPHORUS AS AMENDMENTS FOR MINESOILS ON THE CUMBERLAND PLATEAU[1].

by

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Abstract. A study was conducted to evaluate the benefit of applying municipal sewage sludge and/or phosphorus on surface mined land on the Cumberland Plateau in Fentress County, Tennessee. The objective of the study was to evaluate minesoil fertility and plant response after treatment. The site was prepared according to surface mine regulations and sampled before and after treatment. The experiment was conducted as a split, split, split block arranged in a randomized complete block design with four replications. Each replication contained a sludge treatment, a phosphorus treatment, a sludge/phosphorus combination treatment and a control. Minesoils amended with sludge alone had the greatest increase in fertility and plant response. Phosphorus alone had a comparable, though slightly lower response of plant growth on the sludge. Legume species responded particularly well on phosphorus. A combination of sludge and phosphorus had a slightly suppressive effect on some plant growth responses compared to sludge alone.

Additional Key Words: Minesoil Fertility, Sludge Application, Revegetation.

Introduction

The impact of surface mining for coal on the land is a major environmental concern. Surface mined land has been reclaimed to the standards of the Surface Mine Reclamation Act of 1977 (Wagner, 1979) since its inception. New soils created after the surface mining processes range from highly acid to neutral pH values. Soils that are highly acid have high concentrations of Al and Mn. Additionally, these soils contain low levels of N, P and organic matter (OM). Researchers have reported that these conditions are detrimental to plant growth and corrective measures should be employed for successful establishment of vegetation (Fribourg *et al.*, 1981; Lyle, 1987; Sopper and Seaker, 1990). Spoil from the "high-sulfur" coal of the eastern U. S. containing various forms of pyrite (FeS_2) must be limed sufficiently to counteract the continuing formation of sulfuric acid. Within two years spoil will become too acid to support a satisfactory vegetative cover if not limed sufficiently (Sopper and Seaker, 1990).

An alternative to standard fertilization is to use municipal sewage wastes. Halderson and Zenz (1978) reported that typical plant nutrient analyses of municipal sewage wastes is as follows; N = 5% ; P = 2.5%; and K = 0.4% (on % dry matter basis). Advantages of reclamation with sewage sludge are the rapid incorporation of OM and plant nutrients into the minesoil (Loehr *et*

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al., 1979).

Studies in Pennsylvania showed that applying sludge to minesoils enhanced seed germination and vegetative growth (Loehr *et al.*, 1979). A study of sludge application on revegetated minesoil in West Virginia indicated that grass density and biomass increased with increased application of sludge, while numbers and biomass of legume species decreased (Skousen, 1988). Data and observations on the Fentress County mine site (Walker, 1993) confirmed this observation.

Sludge provides an immediate addition of OM and microorganisms to the soil. Natural accumulation of organics usually takes many years to complete. Municipal sludges also contain varying quantities of the needed P from detergents and other sources and could supply up to 27% of the P needed in agriculture (Sommers and Sutton, 1980; Suss, 1981). The P available to plants in sludge varies from 20-100% compared with 100% in monocalcium phosphate (Haan, 1981). However, the larger quantities of P, N and OM in municipal sludge could counteract the chemical binding of P that takes place due to poor minesoil conditions.

Moisture stress causes P to be unavailable to plants (Ozanne, 1980). The OM in sludge helps the soil retain moisture, which could aid P availability. Sludge stabilized by heavy lime treatment can have value as a liming agent as well as by adding organics and N (Jacobs, 1981). Application of limed sludge must be carefully controlled as excessive quantities of limed sludge can create pH levels that are too high and conditions detrimental to plant growth (Morel, 1981; Walker, 1993).

Minesoils are often moderately to extremely deficient in P which is an important plant nutrient for establishing most plant species (Fribourg *et al.*, 1981; Buck and Houston, 1986). The low pH of some minesoils binds P to Al and Fe in chemically insoluble forms unavailable for plant use. Phosphate dissolved in H_2SO_4 (a by-product of pyrite oxidation in acid minesoil) is too strongly bound to Fe and Al oxides for plant uptake (Hani *et al.*, 1981). The addition of P to the soil is particularly helpful in the initial establishment of vegetation, especially when legumes are desired.

The objective of this study was to evaluate the benefit to plant growth and soil fertility of applying municipal sewage sludge and/or P on surface mined land in Tennessee.

Materials and Methods

Site Location

The experiment was located on the Cumberland Plateau in Fentress County approximately 2 miles south of Jamestown, TN and west of state highway 127 at an approximate elevation of 1600 ft. above mean sea level (Fig. 1). The study site was a 3.5 acre portion of an area that had been surface mined for bituminous coal by the Meta-Elkhorn mining company. Approximately 25-30 ft. of overburden was removed to reach the Nemo coal seam. The minesoils were dominately a fine sandy loam texture containing weathered sandstone, coal, and shale fragments (Branson *et al.*, 1991).

Geology and Soils

The study area was located on the Cumberland Plateau overthrust containing Pennsylvanian age sandstone and shale (Stearns, 1954). The Crab Orchard Mountain group (Rockcastle conglomerate) was identified as the sandstone removed during the mining. The Rockcastle formation is characterized as a sandstone with a shaly unit and coal horizon which occurs approximately in the middle of the formation.The native soils on the Cumberland Plateau are Ultisols and Inceptisols that have formed in residuum in the Pennsylvanian sandstones and shales, or in colluvium from sandstone and shale. The dominant soils are 2 to 4 feet deep over rock (Springer and Elder, 1980) well drained, loamy, strongly acid, and low in natural fertility especially with respect to phosphorus (Jared, 1972).

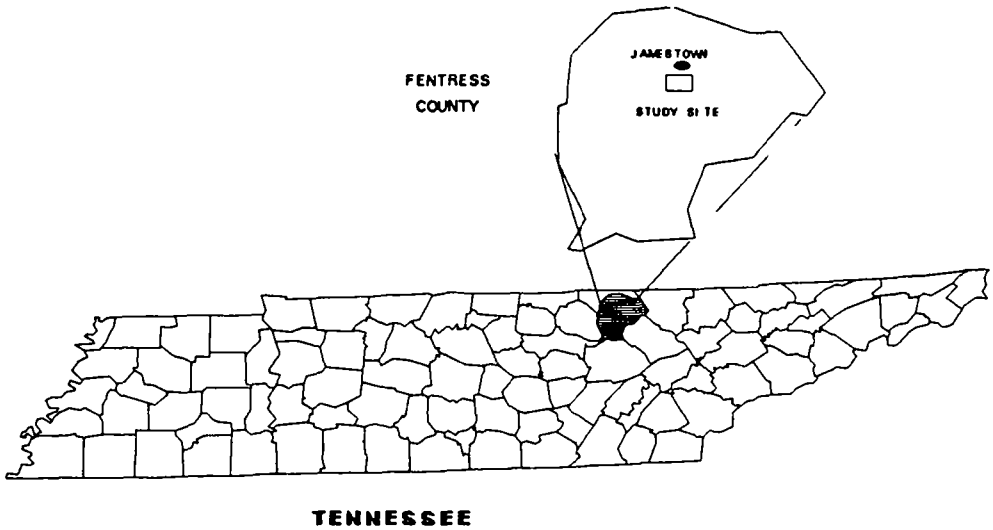

Figure 1. A map showing the study site, located in Fentress County, Tennessee.

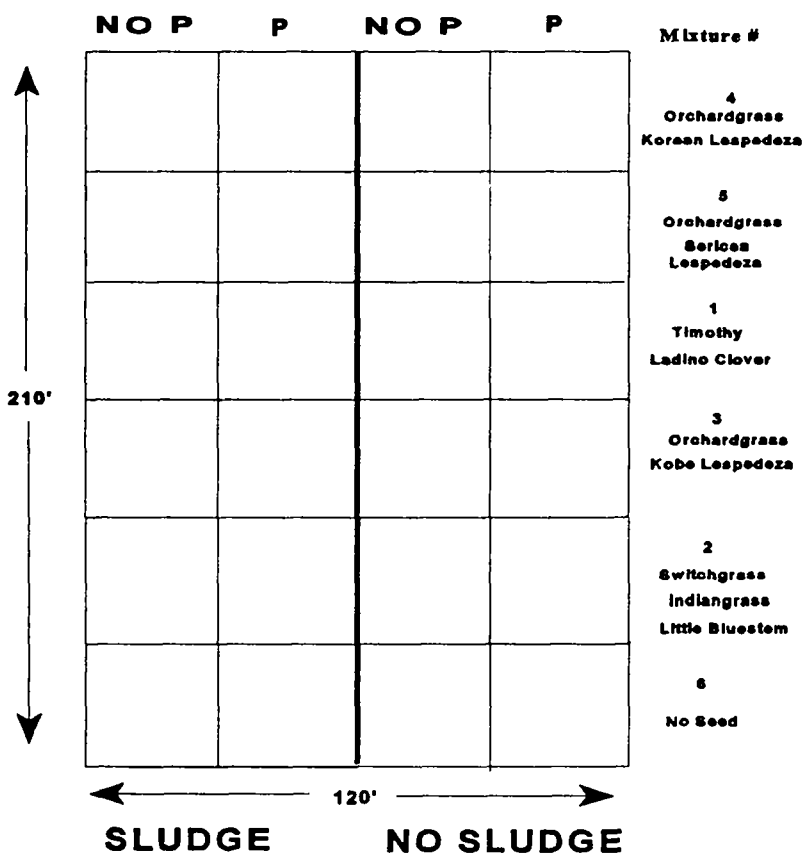

Figure 2. Schematic design of a representative experimental block containing the randomly located sludge and P amendments and seed mixtures.

Field Methods

The study site was prepared and limed by the mine company according to surface mine reclamation regulations prior to installation of the research plots and soil amendments (Wagner, 1979). The research area was divided into four blocks, each measuring 210' long and 120' wide, for the experiment. Figure 2 shows a representative experimental block. Eight soil samples were collected at 6 inch depths from within each split block and combined into bulk samples prior to soil amendment. One-half of three blocks was amended with open-air, composted sludge from Rockwood, Tennessee. One-half of one block was amended with limed, dewatered, municipal sewage sludge from Knoxville, Tennessee. Acquisition difficulties necessitated the use of sludges from two sources. One-half of each block was left unamended by sludge. Bulk samples were collected from each load of sludge before it was applied to the site. The sludge was dumped at rates varying from 8 to 16 tons per acre depending on the amount in the truck (1 truck load was applied to each block), spread with a box grader, and incorporated into the minesoil to a depth of 6 to 8" by discing. It was not possible to incorporate uniform quantities of sludge throughout the sludge blocks. After the sludge was applied, triple superphosphate $Ca(H_2PO_4)_2$ was applied by a cyclone hand spreader to half of each sludge strip and half of each unamended strip at a rate of 50 lbs P/acre .

The statistical design was a split, split, split block with 4 replications. Each replication contained 4 different soil amendments and 6 seed treatments in 30' by 35' plots (Fig. 2). Each replication contained a sludge amendment, a P amendment, a sludge + P combination amendment and an unamended-limed control applied in randomly selected strips. Plots were then seeded in randomly selected strips across all amendments with one of the following five seed mixtures.

1) Ladino clover, *Trifolium repens*, timothy, *Phleum pratense* (LDT)
2) Switchgrass, *Panicum virgatum*, indiangrass, *Sorghastrum nutans*, little bluestem, *Schizachyrium scoparium* (WSG)
3) Kobe lespedeza, *Lespedeza striata*, orchardgrass, *Dactylis glomerata* (KBO)
4) Korean lespedeza, *Lespedeza stipulacea*, orchardgrass (KRO)
5) Sericea lespedeza (A. U. Lotan), *Lespedeza cuneata*, orchardgrass (AUO)
6) No Seed Control (NS)

Vegetation was identified and percent cover was estimated visually in five one square foot quadrats within each plot post-amendment in 1989 and 1990. Soil samples were collected to 6 inch depths and combined as a bulk sample from each half block preamendment in 1989. A soil sample was collected from each seed plot and combined as a bulk sample from within each amended and unamended strip in each block in 1990.

Sample Analysis

The blocks were mapped for areas of light to heavy sludge content and this information was considered in the plant statistical analysis. Chemical analyses were performed on the soil samples and statistical analyses (SAS General Linear Models and Least Squares Means) were performed on the soil and vegetation data (SAS, 1989).

Soil and Sludge pH. The pH was measured in the laboratory on representative samples of the sludges applied to the minesoil. The sludge from Rockwood, TN had an average pH of 6.2. The sludge from Knoxville, TN had an average pH of 11.0. The pH was measured on each of the soil samples taken at the site (Southern Cooperative Series, 1974).

Cation Analysis. Soil samples were extracted using the Mehlich I soil test (Baker and Amacher, 1982; Southern Cooperative Series 1974). The extracts were analyzed for P, Ca, K, Mg, Cu, Zn, Mn, and Fe on an Inductively-Coupled Plasma Spectrophotometer (Shugar and Dean, 1990).

Results and Discussion

Observation of the study site in

June 1989, (one month after treatment and seeding) revealed dramatic differences in vegetative response among amendments. Seeds on unamended control areas had germinated, but plants were very sparse and severely stunted. Plants on P amended plots had germinated well and showed fair to good growth depending on the species. Sludge treated areas showed dense, luxuriant growth, in part due to heavy weed and tomato seed contamination of the open-air composted Rockwood sludge. The lime-stabilized, dewatered Knoxville sludge had no weed seed contamination, possibly due to high pH, and the applied experimental seeds germinated well. Excessive applications of lime-stabilized sludge were apparently toxic to the plants as no seeded species germinated in isolated spots of excessively concentrated Knoxville sludge. It appeared that P application greatly enhanced performance of all the legume species (Fig. 3). Grass species such as timothy and orchardgrass grew much more vigorously on sludge amended areas than on the other amendments. Unseeded controls had very sparse growth on all amendments, but volunteer species were present even on unamended plots. The plots amended with the combination sludge + P had slightly less cover than those amended with sludge. All treatments except the unamended plots resulted in 60 to 90% cover in 1990 (Fig.4). Grasses were more vigorous on sludge treated soils while legumes were predominant on P treatments. The percent cover of all seed mixtures on the combination (sludge + P) amendment remained slightly lower than the same mixtures on sludge alone, perhaps due to chemical toxicity or binding of needed phosphorus or other nutrients.

Table 1 shows minesoil fertility analyses on experimental plots before and after treatment. Values for pH on preamendment plots ranged narrowly between 5.1 to 5.2 for the plots. Ca averaged 228 lbs/a. Phosphorus concentrations ranged from 0.5 to 3.4 lbs/a, near the lower end of detection limits. K averaged 67 lbs/a and Mg 50 lbs/a.

Table 1 shows a dramatic increase in the Ca values between the preamendment analysis in 1989 (228 lbs/a) and the unamended control for 1990 (2169 lbs/a) which was attributed to the addition of lime during site preparation. Lime increased the pH of the unamended control plots to an average of 6.3. P and K levels showed little change from the preamendment levels after lime application. K levels were low for legumes and plants that germinated on limed, unamended plots were severely stunted. Mg levels were an average of 47 lbs/a higher after the addition of lime.

Effect of amendment on soil fertility

All soil fertility levels measured were higher on minesoil amended with P than on the limed, unamended control (Table 1). However, these changes were not significant at the $p \leq 0.05$ level. Statistical analysis of the differences between the preamendment (prior to lime and soil amendment) fertility levels of 1989 and the limed, P-amended fertility levels of 1990 for all nutrients showed no significance (Table 2). Minesoils amended with sludge had higher P levels by 244 lbs/a compared to the unamended control and 215 lbs/a compared to the P amendment (Table 1). These differences were significant at the $p \leq 0.05$ level. K levels on sludge plots were similar to levels on the unamended control and on P amendments. Ca and Mg levels were not significantly higher on sludge than on the other soil amendments. Statistical analysis of the differences in the preamendment (prior to lime and soil amendment) fertility levels from 1989 and the limed, sludge-amended levels from 1990 show P levels to be significantly higher on the sludge amendment at the $p \leq 0.05$ level (Table 2).

The combination sludge + P amendment exhibited a reduction of P and Mg, when compared to the sludge amendment, possibly due to inconsistent sludge application (Table 1). However, the percent cover of vegetation was lower on the combination amendment than the sludge with the application error considered. Statistical analysis of soil fertility showed no significant effect of the combination amendment on any nutrients

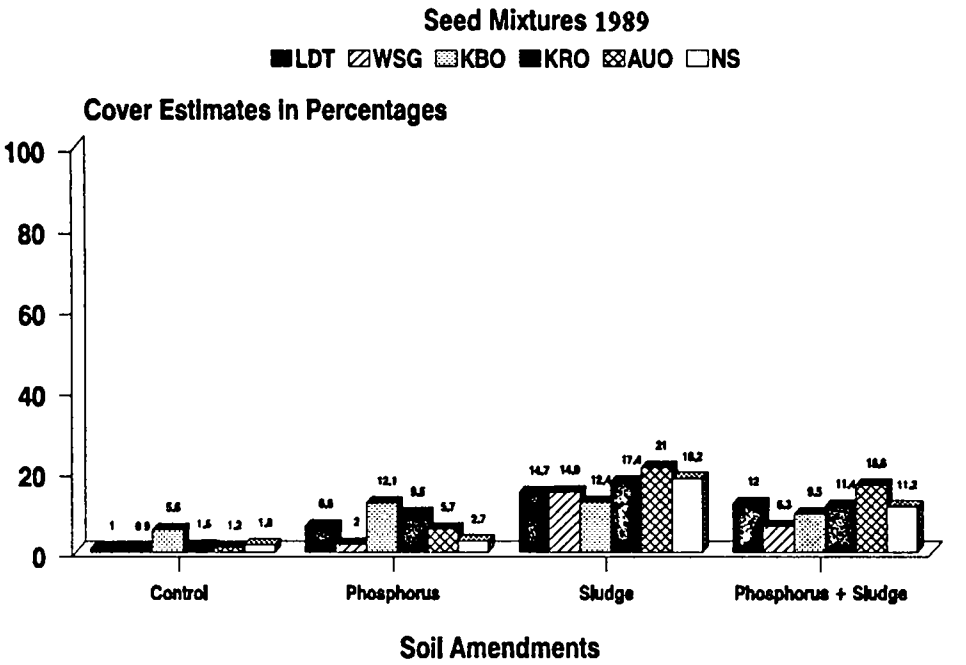

Figure 3. Mean percent cover estimated visually for each wildlife seed mixture relative to soil amendments during the first growing season in 1989. Abbreviations defined in Field Methods.

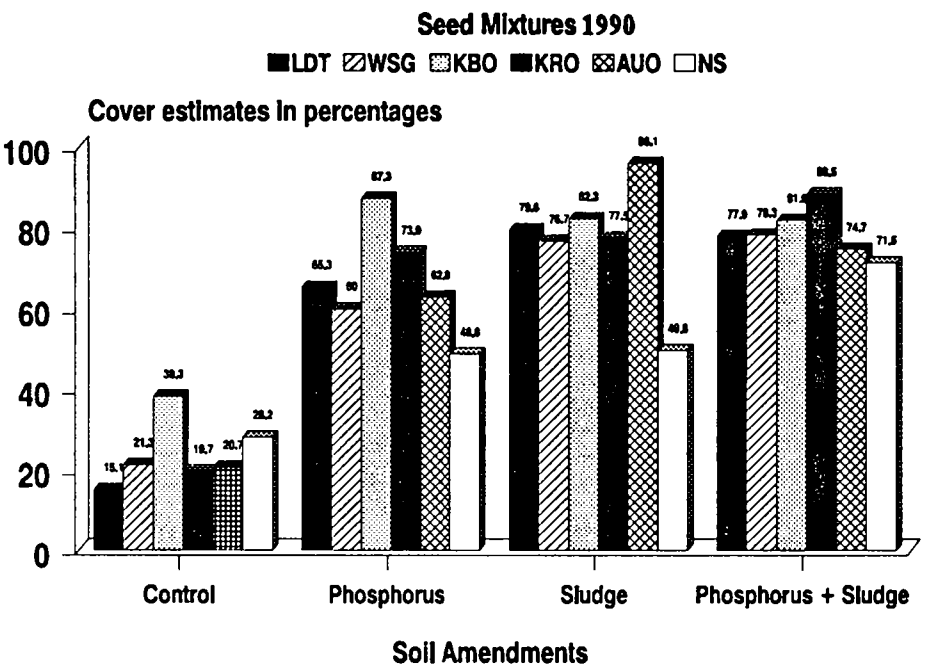

Figure 4.Mean percent cover estimated visually for each wildlife seed mixture relative to soil amendment during the second growing season in 1990. Abbreviations defined in Field Methods.

Table 1: Minesoil fertility analysis in 1989 before liming and soil amendments and in 1990 after liming and soil amendments. N=4.Least squares means ± standard error are shown.

	Lbs/A				
Amendment	Ca	P	K	Mg	pH
Preamend[θ]	228 ± 50	2 ± 0.5	67 ± 2	50 ± 3	5.2 ± 0.02
Control[1]	2169 ± 632	3 ± 46	77 ± 8	97 ± 18	6.3 ± 0.16
P	3675 ± 706	31 ± 52	90 ± 9	144 ± 20	6.5 ± 0.18
Sludge	4280 ± 815	246 ± 60*	86 ± 11	173 ± 23	6.5 ± 0.21
S + P	4007 ± 706	99 ± 52	79 ± 9	138 ± 20	6.7 ± 0.18

*Significant differences in soil fertility due to soil amendment based on Type III SS PR>F ≤0.05
[θ]Nutrients before application of lime and soil amendments.
[1] Unamended, limed control. Statistics do not include preamendment values.

Table 2: Differences in minesoil fertility of plots between 1989 and 1990 (Amended minus unamended). N=4. Least squares means + standard error are shown.

	Lbs/A				
Amendment	Ca	P	K	Mg	pH
Control	1919 ± 606	1 ± 46	11 ± 12	47 ± 18	1.1 ± 0.19
P	3457 ± 677	28 ± 52	23 ± 13	98 ± 20	1.4 ± 0.21
Sludge	4088 ± 782	243 ± 59*	18 ± 15	122 ± 23	1.3 ± 0.24
S + P	3769 + 677	97 + 52	12 + 13	85 + 20*	1.6 + 0.21

*Significant differences in soil fertility due to soil amendment based on Type III SS PR>F ≤ 0.05.

compared to the limed control. Statistical analysis of the differences in the preamendment (prior to lime and soil amendment) fertility levels from 1989 and the limed, combination amended levels from 1990 showed Mg levels significantly higher on the combination amendment at the $p \leq 0.05$ level (Table 2). Differences in the other nutrient levels were not significantly affected by the combination amendment.

Effect of soil amendment on heavy metals

Heavy metals were present in small quantities prior to soil amendment in 1989 (Table 3). Preamendment Cu levels averaged 0.75 lbs/a, Fe averaged 64 lbs/a, Mn averaged 27 lbs/a, and Zn averaged 4 lbs/a. Pb and Cd levels were too low to detect in all samples analyzed. The post amendment data for the 1990 limed, unamended control show heavy metal levels on all control plots decreasing slightly from the preamendment levels (Table 3). None of the changes in heavy metal concentration between the limed control and the P amendment were statistically significant (Table 3). Differences in heavy metal concentrations from preamendment (prior to lime and soil amendment) levels in 1989 to post-amendment levels in 1990 did not change significantly with the application of P (Table 4). Minesoils amended with sludge had Cu levels 9.0 lbs/a higher than the unamended control ($p \leq 0.05$) and 8.8 lbs/a higher than the phosphorus amendment ($p \leq 0.05$) (Table 3).

Sludge amendment had no significant impact on the levels of Fe. Sludge had significantly higher levels of Mn and Zn compared with the unamended control and the P amendment. Copper and Zn levels were significantly higher on sludge plots after lime and sludge were applied ($p \leq 0.05$) (Table 3). Mn levels were significantly lower on sludge ($p \leq 0.05$) than the preamendment levels. Application of sludge and lime did not significantly change Fe levels.

Minesoils amended with the combination sludge + P amendment contained lower levels of Cu and Mn and much lower levels of Zn compared to the sludge amendment, possibly due to inconsistent sludge application (Table 3). There was no significant effect of the combination amendment on any heavy metal concentrations compared to the unamended control. Statistical analysis of the differences between preamendment (prior to lime and soil amendment) metal levels in 1989 and post-amendment levels in 1990 indicated no significant differences on the limed, combination amendment from preamendment levels (Table 4).

Phosphorus as a Soil Amendment

P application in this study enhanced the establishment of vegetation. Plots amended with P in Fentress County were visibly higher in vegetative cover and the plants were more vigorous than plants on unamended control plots in both growing seasons (Figures 3 and 4). The P amendment was sufficient to establish vigorous stands of all the species of legumes in the legume/grass seed mixtures planted. P application in this study resulted in higher initial vegetative response. Other studies have shown that continued applications of P are required to maintain long term stands (Barnhisel *et al.* 1979).

The legumes on P amended plots will add N and, eventually, OM to the minesoil. However, this will occur more slowly than with organics supplied through the addition of municipal sludge. Ca, Mg and K fertility levels were increased with the application of triple superphosphate $Ca(H_2PO_4)_2$. Triple super phosphate contains 20% Ca, which explains the increase in Ca levels seen on P amended plots (Lyle, 1987). K levels were similar on all three soil amendments ,though slightly lower on the sludge + P amendment.

Municipal Sludge as a Soil Amendment

Previous studies of fertilization with sewage sludge have indicated that equal or better long

Table 3: Minesoil heavy metal analysis in 1989 before liming and soil amendment and in 1990 after liming and soil amendments. n=4.Least squares means ± standard error are shown.

	Lbs/A			
Amendment	Cu	Fe	Mn	Zn
Preamendment[e]	0.76 ± 0.03	63 ± 4	27 ± 1	4.2 ± 0.3
Control[1]	0.68 ± 1.41	52 ± 11	14 ± 4	3.3 ± 16
Phosphorus	0.82 ± 1.58	48 ± 12	19 ± 4	3.9 ± 18
Sludge	9.66 ± 1.82*	46 ± 14	30 ± 5*	100.3 ± 21*
Sludge + P	3.97 + 1.58	50 + 12	26 + 4	31.1 + 18

*Significant differences in heavy metal concentration due to soil amendment based on type III SS PR>F ≤0.05.
[e]Nutrients before application of lime and soil amentments.
[1]Unamended, limed control. Statistics do not include preamendment values.

Table 4 Changes in minesoil heavy metal concentration between 1989 and 1990 (Amended minus Unamended). N=4. Least squares means ± standard error are shown.

	Lbs/A			
Amendment	Cu	Fe	Mn	Zn
Control	-0.09 ± 1.42	-16.4 ± 14.6	-12.4 ± 5.4	-0.7 ± 16
Phosphorus	0.04 ± 1.58	-19.0 ± 16.3	-9.0 ± 6.0	-0.5 ± 13
Sludge	8.90 ± 1.83*	-9.3 ± 18.9	-1.3 ± 6.9*	95.8 ± 21*
Sludge + P	3.23 + 1.58	-10.8 + 16.3	-1.8 + 6.0	27.2 + 13

*Significant differences in heavy metal concentration due to soil amendment based on Type III SS PR>F ≤ 0.05.

term benefits may be derived from the incorporation of sludge than from traditional fertilizers (Hani *et al.*, 1981; Larsen, 1981; Vogel, 1981; Wolt, 1985). Analyses of percent cover in this study support this contention (Figures 3 and 4). Vegetative cover was consistently greater on sludge and combination sludge + P plots than on P or unamended plots. Orchardgrass was more competitive than lespedeza species on the sludge and sludge + P combination amendments than on P. Timothy densities were greater than those of ladino clover on sludge amended plots. Vegetative growth and cover were improved on sludge plots relative to the other amendments with all seed mixtures, including the unseeded control (amendments and seed mixtures defined in Field Methods). The relatively high cover values on the unseeded sludge plots were due to high concentrations of weed seeds present in the Rockwood sludge. Unseeded controls on sludge and combination plots had greater vegetative cover than unseeded controls on unamended plots and P plots. Improved soil conditions of higher fertility, organics, and better moisture retention on sludge and combination plots encouraged the appearance and growth of volunteer plant species, including tree seedlings such as tulip poplar, maple, and cedar.

Conclusions

1. Minesoil acidity was reduced from preamendment levels by the application of lime. The P, sludge, and combination amendments further reduced acidity.
2. All nutrient levels were higher on the P amendment than on the limed control.
3. A greater quantity of nutrients was detected on minesoil amended with sludge than on the other amendments.
4. The combination sludge + P amendment exhibited a lower level of all nutrients and slightly less vegetative cover compared to the sludge amendment.
5. Lime application reduced heavy metal levels from preamendment levels.
6. A single application of 16 tons/a of municipal sludge did not add unacceptable levels of heavy metals.
7. The combination sludge + P amendment had lower heavy metal levels than the sludge amendment with the exception of iron.
8. The sludge amendment had greater vegetative cover than all other amendments in the first growing season.
9. Percent cover on the P, sludge and combination amendments increased, with less difference between amendments, in the second growing season. All amendments had greater cover than the control.

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A RECLAMATION APPROACH FOR MINED PRIME FARMLAND BY ADDING ORGANIC WASTES AND LIME TO THE SUBSOIL[1]

by

Qiang Zhai and Richard I. Barnhisel[2]

Abstract. Surface mined prime farmland may be reclaimed by adding organic wastes and lime to subsoil thus improving conditions in root zone. In this study, sewage sludge, poultry manure, horse bedding, and lime were applied to subsoil (15-30 cm) during reclamation. Soil properties and plant growth were measured over two years. All organic amendments tended to lower the subsoil bulk density and increase organic matter and total nitrogen. Liming raised exchangeable calcium, slightly increased pH, but decreased exchangeable magnesium and potassium. Corn ear-leaf and forage tissue nitrogen, yields, and nitrogen removal increased in treatments amended with sewage sludge and poultry manure, but not horse bedding. Subsoil application of sewage sludge or poultry manure seems like a promising method in the reclamation of surface mined prime farmland based on the improvements observed in the root zone environment.

Additional Key Words: sewage sludge, poultry manure, horse bedding, liming, corn, forage.

Introduction

The use of organic amendments for mine spoil reclamation has been extremely successful (Seaker and Sopper, 1984) because of its immediate improvement of soil chemical, physical, and biological conditions, acceleration of plant establishment and growth, and achievement of long-term productivity. However, the results may be different for prime farmland reclamation because the soil physical, chemical, and biological properties of prime farmland are different from mine spoils. Currently, there are few studies that have quantitatively measured the effect of organic waste application to reclaimed prime farmland on soil properties and crop response.

Amending subsoil with organic wastes, such as sewage sludge, and lime may eliminate major factors limiting plant growth. Low amounts of available essential nutrients and extreme acidity (Dancer and Jansen, 1987), have been implicated in limiting post-mine plant growth. Subsoil acidity may be and important yield limiting factor (Sumner et al., 1986). It restricts roots from penetrating deeply into such soils (Adams and Moore, 1983). Organic amendments to subsoil may also decrease bulk density. Subsoil compaction often occurs during soil replacement by heavy equipment. Studies on the rooting behavior of row crops in mined soils of southern Illinois (Grandt, 1988) showed the plant root system was confined to the topsoil layer as a result of the adverse physical and structural

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properties of the subsoil. This, in turn, resulted in greater weather sensitivity for corn, resulting in significant yield reductions. Numerous studies have been reported which indicated that subsoil compaction during soil reconstruction by heavy equipment was an important factor limiting the postmine productivity for certain crops, especially row crops (Barnhisel, 1988).

The objectives of organic wastes and lime applications to subsoil for prime farmland reclamation are: (1) to enhance soil organic matter content and nutrient cycling in disturbed subsoil; and (2) to eliminate major factors limiting plant growth by improving subsoil properties.

Materials and Methods

Field procedures

This prime farmland was mined by TDC Coal Co. in Webster County, western Kentucky. The topsoil and subsoil were stored as separate stockpiles for two years. The soil series was the Loring (fine-silty, mixed, thermic Typic Fragiudalfs). The original topsoil and subsoil were replaced separately in the summer of 1990.

Prior to the application of the organic wastes to subsoil, the area was divided into two equal blocks (121.6 x 36.6 m) and agricultural grade limestone was applied at rate of 22.4 Mg ha^{-1} to one block. This lime rate was needed to raise the pH of 30 cm of subsoil to 6.5. Sewage sludge (33.6 Mg ha^{-1}), poultry manure (22.4, Mg ha^{-1}), and horse bedding (112 Mg ha^{-1}) were applied as separate treatments to the subsoil (plot size 30.4 x 36.6 m) prior to topsoil replacement. An control plot with the same size was also included for comparison. The rate of 33.6 Mg ha^{-1} for sewage sludge was the upper limit based on current regulations of N applied for "land farming" under the specifications associated with "permit by rule". The rate of poultry manure was based on recommendations of N need for corn when added to the soil surface (Steele, et al., 1982). The application rate for horse bedding was calculated to provide the same amount of total N as the poultry manure. All organic wastes and lime were incorporated into 0-15 cm of the subsoil with a chisel plow. Then topsoil (15 cm) was placed on the prepared subsoil. The entire area was broadcast with a mixture of alfalfa (*Medicago sativa* L.), red clover (*Trifolium hybridum* L.), and tall fescue (*Festuca arundinacea* Schreb.) on 17 August 1990 at seeding rates of 10.2, 10.2, and 18.2 kg ha^{-1}, respectively.

In May 1991, the limed and unlimed blocks were each divided into two equal parts. One part was sprayed with a mixture of atrazine (4WDL) and 'Roundup' at rates of 3.0 and 1.8 L ha^{-1}, respectively, then corn (*Zea mays* L.) was planted at seeding rate of 59,000 kernels ha^{-1}, Corn was also planted the following year on 25 May. In 1993, the forage was killed by atrazine and 'Roundup' and entire area was planted to corn. Fertilizer was applied uniformly to corn each year. Nitrogen, P, and K fertilizers were surface broadcast at rates of 165, 120, and 120 kg ha^{-1}. These blocks were further divided into four subblocks (4.75 x 30.4 m) for multiple yield measurements and observations of soil preperties (not true replications). Subsoil (15-30 cm) was sampled using a tractor-mounted Giddings coring machine for determination of physical and chemical properties on 15 June of 1991, 8 July 1992, and 20 November 1993 for biological properties.

Soil analyses

Soil bulk density was determined by Blake and Hartge, except that the core size was 4.25 cm (1986). Water-holding capacity was determined using the method developed by Klute (1986).

Four separate samples were collected from the subblocks (4.75 x 36.6 m) within each waste treatment. The soil samples for chemical analyses were air-dried, and ground to pass a 2-mm sieve. Soil pH was determined with a pH meter on a 1:1 deionized water to soil mixture (McLean, 1982). Exchangeable Ca, Mg, K, and Na and CEC were determined with the neutral 1 M NH_4OAc method (Thomas, 1982). Available P was determined using the Bray-I (Bray and Kurtz, 1945) which has been commonly used in Kentucky for disturbed land. Organic matter (Nelson and Sommers, 1982) and total nitrogen (Bremner and Mulvaney, 1982) were performed by the University of Kentucky Soil Testing Laboratory, Division of Regulatory Services.

Soil microbiological analyses were performed using moist soils. Total heterotrophic and facultative anaerobic organisms were enumerated by the Most Probable Number method (Alexander, 1982). Microbial biomass (C) was determined using a chloroform fumigation procedure (Parkinson and Paul, 1982). Soil respiration rate (CO_2 evolution rate) in the laboratory was measured by gas chromatography on a Varian 3700 gas chromatograph equipped with Porapak Q column operated at 80°C (Rice and Smith, 1982).

Plant analyses

Forage tissue (five samples collected for each treatment) and corn ear-leaf (four samples collected for each treatment) were sampled and dried under vacuum at 65°C. These samples were ground with a Thomas-Wiley mill, pass a 0.425 mm sieve and stored in plastic bags. The samples were then analyzed for N, P, K, Ca, and Mg. Nitrogen and P in plant tissue were determined based on the micro-Kjeldahl method as presented by Jones and Case (1990). Potassium, Ca, and Mg were determined using the nitric-perchloric wet-ashing procedure (Jones and Case, 1990). Element concentrations were determined using an Instrumentation Laboratory S 11 Atomic Absorption Spectrometer.

Statistical analyses

Statistical analyses were performed using the Statistical Analysis System (SAS Institute, 1985). The General linear Model (GLM) procedure was used to obtain the analyses of variance.

Results and Discussion

Soil response

Selected physical and chemical properties of subsoil (15-30 cm) are shown in Table 1 for 1991 and Table 2 for 1992. Subsoil bulk densities were reduced by all organic treatments compared to check plots in 1991. The horse bedding treatment had a lower bulk density than the control in 1992 (two years after waste application) compared to other organic treatments. All three organic amendments increased the recent organic matter, total N, and Bray-P in 1991 and 1992. However, organic amendments generally did not affect water holding capacity, CEC, and exchangeable bases (Ca, Mg, K, and Na). Liming significantly increased exchangeable Ca, but pH and CEC were not significantly increased. Subsoil liming also tended to decrease exchangeable Mg and K, but there were no significant differences between limed and unlimed treatments.

Total soil heterotrophic and facultative anaerobic organisms, microbial biomass C, and respiration rates are given in Table 3. Total heterotrophic and facultative anaerobic organism population, biomass C, and respiration rate were still higher than the check after three years following waste application. The horse bedding treatment had significantly high values among these microbiological parameters. This was probably due to the high amount of carbon added to the subsoil

Table 1. Physical and chemical properties affected by organic wastes and lime application to subsoil (15-30 cm) on 15 June 1991.

Trt	BD† (g/cm^3)	WHC (%)	pH	OM (%)	TN (---mg/kg--)	Bray-P	CEC (--------	Ca	Mg	K	Na
							coml(+)/kg	---	------)		
SS	1.35^b	22.0^a	4.83^a	1.10^b	740^b	16.0^a	11.6^a	6.01^a	1.18^a	0.16^a	0.09^a
PM	1.30^b	20.7^a	4.99^a	1.41^b	766^b	21.6^a	12.1^a	6.19^a	1.38^a	0.20^a	0.11^a
HB	1.19^c	23.4^a	6.07^a	2.31^a	933^b	15.6^a	11.2^a	6.59^a	1.52^a	0.35^a	0.14^a
CK	1.55^a	24.5^a	4.51^a	0.84^b	466^b	3.4^b	11.8^a	5.08^a	1.03^a	0.17^a	0.09^a
UL	1.34^a	23.8^a	4.67^a	1.52^a	747^b	13.3^a	11.5^a	5.22^a	1.48^a	0.23^a	0.12^a
L	1.35^a	21.5^a	5.53^a	1.29^a	705^b	15.0^b	11.8^a	6.71^a	1.07^a	0.21^a	0.09^a

† BD, bulk density; WHC, water holding capacity; OM, organic matter content; TN, total nitrogen content; SS, sewage sludge; PM, poultry manure; HB, horse bedding; CK, check plot; UL, unlimed; and L, limed treatment. Comparison within the same column at $p<0.1$.

Table 2. Physical and chemical properties affected by organic wastes and lime application to subsoil (15-30 cm) on 8 June 1992.

Trt	BD† (g/cm^3)	WHC (%)	pH	OM (%)	TN (---mg/kg--)	Bray-P	CEC (--------	Ca	Mg	K	Na
							coml(+)/kg	---	------)		
SS	1.48^a	24.6^a	6.02^a	1.21^b	852^b	7.8^a	11.5^a	5.73^a	1.40^a	0.18^a	0.10^a
PM	1.51^a	23.4^a	6.84^a	1.37^b	930^b	14.2^a	12.0^a	6.74^a	1.51^a	0.22^a	0.14^a
HB	1.37^b	21.6^a	6.40^a	2.32^a	1052^b	13.2^a	11.2^a	6.38^a	1.73^a	0.22^a	0.12^a
CK	1.51^a	23.4^a	6.28^a	0.90^b	685^b	3.7^b	11.0^a	6.10^a	1.50^a	0.19^a	0.08^a
UL	1.43^a	22.5^a	6.21^a	1.64^a	997^a	13.1^a	11.2^a	5.73^b	1.71^a	0.28^a	0.07^a
L	1.51^a	23.9^a	6.56^a	1.26^a	762^a	13.4^b	11.7^a	6.74^a	1.36^a	0.22^a	0.14^a

† BD, bulk density; WHC, water holding capacity; OM, organic matter content; TN, total nitrogen content; SS, sewage sludge; PM, poultry manure; HB, horse bedding; CK, check plot; UL, unlimed; and L, limed treatment. Comparison within the same column at $p<0.1$.

Table 3. Total heterotrophic and facultative anaerobic organisms, microbial biomass, and respiration rates after organic wastes and lime application to subsoil.

Trt	Total Heterotrophs (10^5/g)	Facultative Anaerobes (10^5/g)	Microbial Biomass (C) (mg/kg)	Respiration Rate (mg CO_2/kg h)
Sewage sludge	2.4 b†	0.59 ab	117 b	15.7 b
Poultry manure	3.0 b	0.41 b	103 b	14.1 bc
Horse bedding	11.6 a	0.92 a	187 a	20.1 a
Check	0.1 b	0.06 b	75 b	12.4 c
Unlimed	3.2 a	0.46 a	105 a	15.5 a
Limedb	5.3 a	0.53 a	136 a	15.6 a

† Comparison within the same column at $p<0.1$.

that could have enhanced microbial activity and development. Second attributing factor may be the higher application rate (112 Mg ha^{-1}) compared to the rates used for sewage sludge (33.4 Mg ha^{-1}) and poultry manure (22.4 Mg ha^{-1}). Another possibility is that lower microbial activity in sewage sludge and poultry manure treatments is due to effect of time, these observations were made three years after the wastes were applied. The results would be different if the microbiological activities were observed soon after application of organic wastes. Decomposition and mineralization rates are usually faster, particularly for poultry manure than horse bedding, as most of the sewage sludge and poultry manure materials were mineralized after three years (Zhai et al., 1993). Subsoil liming did not significantly affect microbial activity. This is probably due to that microbial activity and development is usually confined below pH 4.5 (Tate, 1985).

Corn response

Results for corn grain yield, N removal, ear-leaf element concentrations are presented in Tables 4, 5, and 6 for 1991, 1992, and 1993, respectively. The grain yield and N removal were significantly affected by the different subsoil amendments. Yields were generally higher for sewage sludge and poultry manure treatments than for the check. The horse bedding treatment had the lowest yield over all three years. This is likely due to the high C:N ratio of horse bedding reduced N availability (Zhai et al., 1993). Corn plants in the horse bedding plot were more chlorotic, especially during the grain filling period. Reduced N availability in horse bedding treatment was also shown in an N mineralization-immobilization study in which net immobilization was observed (Zhai et al., 1993).

Average corn yields for all treatments were higher in 1992 than 1991 or 1993. The yields of all treatments in 1991 (Table 4) were far below 6.70 Mg ha^{-1} which is the critical value for Phase III bond release of a reconstructed prime farmland. This was due to heavy rain in planting time which reduced seed germination. The late planted corn in 1991 (two weeks later than normal) suffered moisture stress in the growing season, particularly at the grain filling stage during late July and August.

Table 4. Ear-leaf composition, grain yield, and N removal in 1991 as affected by organic waste application and liming of subsoil.

Trt	Ear-leaf N	Ear-leaf P	Ear-leaf K	Ear-leaf Ca	Ear-leaf Mg	Grain Yield	N Removal
	(g/kg)					(Mg/ha)	(kg/ha)
SS†	27.6a‡	2.69a	21.6a	5.89a	2.98a	3.91a	99.2a
PM	25.0a	2.39a	20.1a	5.96a	3.22a	3.35ab	77.1b
HB	20.4b	1.83a	20.3a	5.88a	2.56a	2.31c	58.7b
CK	22.7b	2.03a	19.1a	5.81a	2.97a	3.02bc	58.8b
L	24.4a	2.35a	21.1a	6.05a	3.14a	2.58a	63.1b
UL	23.5a	2.11a	19.5a	5.71b	2.72a	3.72a	83.8a

† SS, sewage sludge; PM, poultry manure; HB, horse bedding; CK, check; L, limed; UL, unlimed.
‡ Comparison within the same column at $p<0.1$.

The ear-leaf N concentration has been repeatedly used as an indicator of the N nutrition of the corn crop (Dirks and Bolton, 1980). Ear-leaf N concentrations found in this study were different, depending on organic amendment. Higher ear-leaf N concentrations were observed for sewage sludge and poultry manure treatments than for the unamended check and horse bedding treatments (Tables 4 and 5). The ear-leaf N concentrations in all organic amendment treatments were generally not much different from that of the check in 1993 (Table 6). Subsoil liming consistently improved ear-leaf N, though not significantly.

Table 5. Ear-leaf composition, grain yield, and N emoval in 1992 as affected by organic waste application and liming of subsoil.

Trt	Ear-leaf N	P	K	Ca	Mg	Grain Yield	N Removal
	(---------- g/kg				----------)	(Mg/ha)	(kg/ha)
SS†	25.7a‡	3.02a	20.2a	3.51a	2.13a	9.57a	ND
PM	23.6b	2.81a	23.7a	3.31a	1.63a	8.92ab	ND
HB	15.9c	2.20a	19.3a	3.03a	1.68a	7.19b	ND
CK	22.8b	2.55a	20.1a	3.14a	1.85a	8.11ab	ND
L	22.8a	2.84a	21.7a	3.40a	1.84a	8.30a	ND
UL	21.2a	2.46a	20.1a	3.09b	1.80a	8.68a	ND

† SS, sewage sludge; PM, poultry manure; HB, horse bedding; CK, check; L, limed; UL, unlimed; ND, not determined.

‡ Comparison within the same column at $p<0.1$.

Table 6. Ear-leaf composition, grain yield, and N removal in 1993 as affected by organic waste application and liming of subsoil.

Trt	Ear-leaf N	P	K	Ca	Mg	Grain Yield	N Removal
	(---------- g/kg				----------)	(Mg/ha)	(kg/ha)
SS†	21.8a‡	2.71a	20.2a	4.23a	2.10a	4.81a	74.0a
PM	21.7a	2.60a	19.5a	3.60a	1.19a	3.40b	57.1b
HB	19.7a	2.50a	19.0a	3.93a	1.95a	2.67b	45.3c
CK	22.0a	2.79a	19.5a	4.23a	1.68a	1.89c	25.8c
L	23.6a	2.87a	19.7a	4.55a	1.97a	3.18a	50.6a
UL	19.0a	2.44a	19.4a	3.45a	1.85a	3.21a	50.4a

† SS, sewage sludge; PM, poultry manure; HB, horse bedding; CK, check; L, limed; UL, unlimed.

‡ Comparison within the same column at $p<0.1$.

Average values for ear-leaf N were similar. Steele et al. (1982) reported critical values of 28.2 g kg^{-1} for ear-leaf N concentration. Dirks and Bolton (1980) found the level of leaf N was a good predictor of corn grain yields, and that the ear-leaf N concentration of adequately N fertilized corn had values in excess of 23 g kg^{-1}. Asghari and Hanson (1984) found higher critical values of ear-leaf N (29.3 g kg^{-1}). In this study, ear-leaf N for horse bedding ranged from 15.9 to 20.4 over three years. This suggests that a N shortage was probably a major yield limiting factor in this treatment.

Potassium, Ca, and Mg were not consistently affected by organic amendments. Subsoil liming increased P and Ca nutrition throughout the three-year period, though not significant. Potassium and Mg were essentially unaffected by liming.

Forage response

Results for forage yield, N removal, tissue element concentrations for first cutting in 1991 and 1992 are presented in Tables 7 and 8, respectively. Because the results of chemical composition were similar to those of second and third cuttings, only first cutting data was presented each year. Yields were generally higher for the sewage sludge and poultry manure treatments than that for the check, but the horse bedding treatment was usually not significantly different from the check across harvests in both 1991 and 1992. Subsoil liming did not significantly affect forage yield and N removal although limed treatments had slightly higher yield and N removal.

In 1991, higher tissue N concentrations were observed for sewage sludge and poultry manure treatments than check plots (Table 7). There was not much difference between the horse bedding treatment and the check plot. Similar results were also observed for the harvest in 1992 (Table 8). Phosphorus concentrations increased in poultry manure and sewage sludge treatments as compared to the check in the first year, but were not as significant as for N. There was not

much difference in P, K, Ca, and Mg concentrations between the horse bedding and the check treatments. Potassium, Ca, and Mg were not consistently affected by organic amendments throughout the study period.

Table 7. Forage tissue, yield, and N removal of first harvest in 1991 as affected by organic waste application and liming of subsoil.

Trt	Forage Tissue N	P	K	Ca	Mg	Forage Yield	N Removal
	(---------- g/kg	----------)				(Mg/ha)	(kg/ha)
SS†	29.7a‡	2.77a	22.7a	2.70a	2.81a	6.36a	189.7a
PM	27.3b	2.34a	19.4a	2.72a	2.73a	5.99a	160.7b
HB	24.9c	2.23b	21.1a	2.70a	2.66a	4.77b	120.1c
CK	25.2c	2.17b	20.2a	2.68a	2.65a	5.22b	130.1c
L	26.8a	2.87a	21.1a	2.83a	2.59a	5.72a	153.8a
UL	26.7a	2.44a	20.5a	2.55a	2.84a	5.45a	146.5a

† SS, sewage sludge; PM, poultry manure; HB, horse bedding; CK, check; L, limed; UL, unlimed.
‡ Comparison within the same column at $p<0.1$.

Table 8. Forage tissue, yield, and N removal of first harvest in 1992 as affected by organic waste application and liming of subsoil.

Trt	Forage Tissue N	P	K	Ca	Mg	Forage Yield	N Removal
	(---------- g/kg	----------)				(Mg/ha)	(kg/ha)
SS†	18.1a‡	3.02a	24.5a	3.19a	2.25a	6.41a	118.3a
PM	20.2ab	3.07a	25.1a	3.80a	2.11a	6.66a	135.1a
HB	13.3b	2.97a	25.9a	3.35a	2.00a	5.66b	75.2 b
CK	13.8b	2.85a	23.8a	3.70a	2.20a	5.97b	82.8 c
L	17.2a	3.11a	24.4a	3.73a	2.10a	6.32a	110.3a
UL	15.5b	2.84a	25.3a	3.34a	2.18a	6.03a	95.2 a

† SS, sewage sludge; PM, poultry manure; HB, horse bedding; CK, check; L, limed; UL, unlimed.
‡ Comparison within the same column at $p<0.1$.

Subsoil liming slightly increased forage tissue N concentrations in 1991 (Table 7). However, liming effects were not significant. Subsoil liming always increased Ca, but did not consistently affect P, K, and Mg.

Overall, the sewage sludge, poultry manure, and horse bedding applications to subsoil tended to lower the subsoil bulk density and increase the soil organic matter and total nitrogen, as well as promoted microbial activities. Surprisingly, subsoil liming produced small increases in subsoil pH and exchangeable Ca, decreased exchangeable Mg and K, and these effects usually were not significant as reported by Sumner et al. (1988). Sewage sludge and poultry manure treatments showed higher N nutrition and yield for corn and forage. Results from this study suggest that subsoil amendments of sewage sludge and poultry manure to reclaim prime farmlands are a beneficial practice in terms of improving some soil properties, particularly N and P status, as well as plant N nutrition and yields.

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