Organic Amendment Effects on Carbon and Nitrogen Mineralization in an Appalachian Minesoil

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(ABSTRACT)

The use of blasted rock overburden as a topsoil substitute during surface-mined land reclamation is practiced in areas with thin, unrecoverable topsoil. The long-term productivity of topsoil substitutes has often been difficult to maintain under forage and row crops. The objective of this project was to evaluate the effectiveness of an unamended topsoil substitute as a tree growth medium compared to both topsoil- and organic matter-amended minesoils based on the accumulation and mineralization of carbon and nitrogen pools. A factorial experiment was established in 1987; treatments (5 cm of a Jefferson series topsoil, 8 cm of whole-tree woodchips, and an unamended control) were assigned to lysimeters filled with blasted overburden. All lysimeters were planted with a tree-compatible ground cover of grasses and legumes and 10 pitch pine *x* loblolly pine hybrid seedlings (*Pinus rigida* L. *x P. taeda* L.). The control treatment was designed based on principles hypothesized as necessary for the success of reclamation forestry; i.e., the selection of a suitable spoil material (slightly acid, low salt concentration), placing that material in an uncompacted (rough-graded) condition, and planting a tree-compatible

ground cover of grasses and legumes. It was hypothesized that, under these conditions, C and N accumulation and N supply would be comparable to topsoil- and organic matter-amended minesoils.

Two years after treatment, net accumulated total organic C in the fine-earth fraction was 4.4, 3.7, and 9.2 g kg^{-1} for the control, topsoil, and woodchip treatments, respectively; after 8 years, concentrations were 12.7, 16.0, and 18.2 g kg^{-1}. Net accumulated total Kjeldahl N after 8 years was 784, 1132, and 679 kg ha^{-1} for the control, topsoil, and woodchip treatments, respectively, but amended minesoils were not significantly different from the control. Total Kjeldahl N accumulation rates were 103, 149, and 89 kg N ha^{-1} yr^{-1}. Aerobic N mineralization potential after 1 year was 31, 63, and 56 mg kg^{-1} for the control, topsoil, and woodchip treatments and increased to 112, 157, and 118 mg kg^{-1} after 8 years.

The woodchip treatment seemed to confer no additional benefits, relative to N accumulation and cycling, compared to the control. The topsoil treatment increased the amount of N and the N mineralization capacity of the minesoil, but did not affect the N accumulation rate or the N mineralization rate relative to the control. While maximum plant productivity would probably be realized in a topsoil-amended minesoil, pine tree volume between the control and topsoil treatments was not significantly different after 5 years.

This study showed that uncompacted, unamended topsoil substitutes of favorable material, planted with tree-compatible grasses and legumes, can provide the necessary conditions for trees and ground cover to survive and grow, and for C and N to accumulate and cycle at levels comparable to amended minesoils. Topsoil substitutes so treated should be able to support and sustain forests for the long-term while minimizing the problem of N deficiency in minesoils. The creation of productive topsoil substitutes helps meet the reclamation requirements for bond release, and can save coal operators grading costs and costs associated with topsoil or organic matter amendments.

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INTRODUCTION

Background

In 1977, Congress passed the Surface Mining Control and Reclamation Act (SMCRA: P.L. 95-87). This law established criteria for the reclamation of land, surface-mined after 1977, by coal operators. Coal operators are required to reclaim surface-mined lands to a level of productivity equal to or greater than the productivity of the land before mining occurred. The coal operator is responsible for meeting all legal reclamation requirements and must post performance bonds that are released in stages as requirements are met. When the coal operator leases the area to be mined from a separate landowner, a conflict can occur between the short-term goals of the coal operator (to perform the most cost-effective reclamation that meets legal obligations) and the long-term goals of the landowner (which may be to achieve and maintain productivity necessary for forest management). The post-mining land use chosen as a reclamation goal has often been hay lands or pasture lands because a grass cover crop is relatively easy to establish. These hay or pasture lands often represent a missed economic opportunity for the landowner because the long-term productivity of reclaimed lands is difficult to maintain for nutrient-intensive forage crops. Deteriorating hay and pasture lands in remote, rugged areas often create erosion hazards and liabilities and will eventually revert to native forest cover. However, this forest will probably be slow-growing and unproductive unless forestry is specifically planned for before and during reclamation. Re-establishment of trees can improve minesoil properties, provide food and habitat for wildlife, and provide an additional source of income through timber harvests or tree crops. Reclamation forestry can provide long-term benefits for landowners and environmental and aesthetic benefits for local communities. For reforestation to be a viable alternative for landowners and coal operators, reclaimed mined land must be capable of supporting productive forests, and reclamation forestry must be cost effective. Consequently, a great deal of research has focused on the forest productivity of minesoils created during the reclamation process.

Surface mining for coal involves the removal of overburden (the soil and rock strata that lie on top of the coal seam) to expose the coal seam. Since the passage of SMCRA, coal mining companies are required to reclaim surface mined land to its approximate original contour (AOC) by returning the blasted rock overburden, or spoil, to the mined area from which it was removed. Any recoverable topsoil must also be returned to the area, and a permanent vegetative cover must be established. When naturally-occurring topsoil is thin or unrecoverable, the coal operator can be granted a topsoil variance that allows the use of blasted rock overburden as a topsoil substitute. The topsoil substitute, or minesoil, must have a demonstrated ability to meet the requirements of the post-mining land use: criteria usually based on certain chemical properties as well as on evidence of past success. Minesoil productivity is determined by the type of mining employed and the reclamation techniques used, particularly overburden selection and placement and type and amount of vegetation.

The long-term productivity of a minesoil for forest vegetation depends, in part, on the ability of the minesoil to accumulate and cycle C and N. Freshly reclaimed minesoils contain little or no organic matter and little C or N in plant-available form. Fertilizer applied at the time of hydroseeding provides enough N and other nutrients to aid in the establishment of the seeded ground cover. However, this nutrient supply is transitory, and high, nutrient-demanding forages often show deficiency symptoms after only a few years.

Traditionally, the approach to establishing pools of C and N has been to replace native topsoil, when available. Since Appalachian topsoils are frequently thin and difficult to recover, there has been some interest in amending minesoils with organic materials such as sawdust or sewage sludge. In contrast to these methods, which involve the placement of a substrate that already includes C and N, another option is to stimulate the establishment of a soil/plant system that builds the C and N pools by natural processes. It is hypothesized that C and N cycles can develop naturally if coal operators select an appropriate spoil type, place it in an uncompacted fashion, establish a tree-compatible ground cover of grasses and legumes, and plant or seed selected tree species. Under the right conditions, this last approach saves the cost of topsoil or organic matter amendments and creates a growth medium where carbon and nitrogen accumulate and cycle and trees and ground cover survive and grow.

Project Purpose

The purpose of this research project was to test the theory that uncompacted, unamended topsoil substitutes of favorable material, planted with tree-compatible grasses and legumes, provide the necessary conditions for C and N to accumulate and cycle, and for early-successional trees and groundcover to survive and grow. Topsoil substitutes so treated can, theoretically, create the conditions necessary to support and sustain forests for the long-term, meet the reclamation requirements for bond release, and save coal operators grading costs and costs associated with topsoil or organic matter amendments.

Project Objectives

The objective of this research project was to evaluate the effectiveness of an unamended topsoil substitute as a growth medium compared to both topsoil- and organic matter-amended minesoils based on the accumulation of adequate C and N pools and the mineralization capacity of these pools. C and N cycling was evaluated based on the changes that occurred over the eight years since the minesoils were created. Specifically, the following null hypotheses were tested:

H_{o1}: The amount of N accumulated in an unamended topsoil substitute is not different from the amount accumulated in minesoils amended with topsoil or organic matter.

H_{o2}: N availability in an unamended topsoil substitute is not different from that in minesoils amended with topsoil or organic matter.

H_{o3}: The amount of C accumulated and mineralized in an unamended topsoil substitute is not different from the amount of C accumulated and mineralized in minesoils amended with topsoil or organic matter and does not affect the ability of a minesoil to mineralize N.

Project Importance

The use of topsoil substitutes saves coal operators money and may increase the productivity of reclaimed mine lands and the economic opportunities of the landowner. The increased rooting depth of properly constructed minesoil systems can increase the productivity over that of undisturbed areas having thin, acidic natural soils. This increased productivity makes commercial forestry a viable option on reclaimed mine lands with the concurrent aesthetic and environmental benefit of reforestation of previously forested areas. Research that indicates that topsoil substitutes can support trees as well as amended minesoils will help ensure that mined land reclamation creates a land base that is a financial and environmental asset for the landowner.

LITERATURE REVIEW

Regulations for the Reclamation of Surface Coal Mined Land

The Surface Mining Control and Reclamation Act (SMCRA) created the Office of Surface Mining Regulation and Enforcement (OSMRE) within the Department of the Interior to enforce the requirements of that and other mining-related laws. OSMRE grants regulatory authority to states with approved reclamation programs and retains regulatory authority for states without approved programs. The state reclamation programs draw heavily from the codified regulations used by OSMRE. An outline of pertinent regulations (found in 30 CFR Chapter VII) follows.

Post-Mining Land Use

The coal operator must have permits for all mining activities undertaken. Permits are granted by the regulatory authority based on detailed mining and reclamation plans submitted by the operator. The post-mining land use is an important part of the mining plan and is usually agreed upon by the coal operator and the landowner. In general, a disturbed area must be restored to conditions capable of supporting the uses of the area prior to mining or higher or better uses (§816.133). Common post-mining land uses include hay/pasture lands, forest lands (commercial and unmanaged), wildlife, and developed lands. The choice of post-mining land use has important implications for the productivity of reclaimed lands. For example, the spoil type and intensive grading practices used during reclamation for hay/pasture lands may be suitable for supporting grasses but may create unsuitable chemical and physical conditions for the growth of trees.

Performance Bonds

After a permit has been approved but before it is issued, the coal operator must file a performance bond payable to the regulatory authority that is conditioned upon the faithful performance of all of the requirements of SMCRA, the regulatory program, and the reclamation plan (§800.11). The period of time for performance bond liability is for the duration of all mining activities, reclamation, and the period of extended responsibility for successful revegetation (§800.13).

The regulatory authority may release the bond in three phases. Completion of Phase I includes completion of backfilling, regrading (including topsoil replacement), and drainage control of a bonded area; 60 percent of the bond may be released for completion of Phase I. After completion of Phase II, which involves the revegetation of regraded areas in accordance with the reclamation plan, an additional amount of the bond may be released. The regulatory authority must retain enough of the bond to cover the cost of reestablishing vegetation by a third party for a period of time specified for operator responsibility. Phase III is concluded when the full period of responsibility for revegetation has passed; at this time, the remaining bond amount may be released (§800.40).

Backfilling and Regrading Requirements

All disturbed areas must be backfilled and graded to achieve the AOC with some important exceptions. Variances from the AOC may occur under conditions of thin or thick overburden, in areas where mining has occurred on previously mined areas, and in areas where the mining method was mountaintop removal (§816.102). The AOC variance for mountaintop removal mining is primarily due to two factors; first, the impracticality of recreating the undisturbed topography with loose spoil material. Second, mountaintop removal mining has the potential to create hundreds of acres of relatively flat land that can support a highly productive, post-mining land use (Daniels and Amos 1984).

Revegetation and Tree Planting

The coal operator is required by SMCRA to reestablish vegetation on all regraded and disturbed areas; this vegetative cover must be in accordance with the approved permit and the reclamation plan. The general requirements state that the vegetative cover must be diverse, effective, and permanent; it must be comprised of native species or of introduced species desirable and necessary to achieve the post-mining land use; it must be equal to or greater than the cover provided by natural vegetation in the area; and, it must be capable of stabilizing the soil surface from erosion (§816.111). In Virginia, the groundcover success standard for herbaceous species in a hay/pastureland post-mining land use is 90 percent; and the stocking requirements for tree species in an unmanaged forest, post-mining land use is 400 trees per acre (§480-03-19.816.116, Virginia Coal Surface Mining Reclamation Regulations, 1981). The period for extended responsibility for successful revegetation begins after the last year of augmented seeding, fertilizing, or other work and continues for five years (§816.116). The period of extended responsibility may continue well past five years if the operator must augment initial efforts because of vegetative failure due to a poor quality growth medium. This is a considerable length of time for a mining company to have large sums of money held up in performance bonds; therefore, coal operators are interested in research that will help them improve the quality of minesoils and ensure revegetation success.

Topsoil and the Topsoil Variance

Minesoils may be constructed using several different materials and several different methods during the reclamation process. The coal operator is required to separate and remove any topsoil before mining when there is sufficient topsoil. The topsoil must be replaced over the regraded mine spoil in a stable and uncompacted condition that will support the post-mining land use. Where there is less than six inches of topsoil, the operator can remove and separate the topsoil and the unconsolidated material immediately below it and treat the mixture as topsoil. Where the topsoil is so thin that it is unrecoverable, or it is of such poor quality that it can not support vegetation, selected overburden materials may be used as a substitute for or as a supplement to topsoil. In this situation, a specific type of minesoil, called a topsoil substitute, is formed from the rock overburden that has been exposed to the mechanical forces of blasting, loading, hauling, and regrading. The blasted rock overburden, or mine spoil, can be considered a "minesoil" when it is exposed to the soil forming factors of climate, vegetation, and time (Daniels and Amos 1984). The operator must prove that the topsoil substitute is equal to or more suitable than the existing topsoil for sustaining vegetation (§816.22).

There are many circumstances, particularly in the coal-producing region of the Appalachians, where topsoil substitutes are used as minesoils. The use of topsoil substitutes can reduce reclamation costs for the coal operator and can create a plant-growth medium more productive than the native soil for the landowner. Opportunities with such potential have naturally generated a large amount of research on the productive capacity of minesoils.

Minesoils and Ecosystem Reconstruction

Minesoils create unique opportunities for scientists interested in soil genesis, and unique problems for those interested in understanding and manipulating the structure and function of minesoils to increase productivity. The skeletal nature of most minesoils means that primary succession is often the starting point for ecosystem reconstruction. Soil development processes like plant establishment, nutrient accumulation in plants and soil, and the development of soil structure and the reduction of toxicities are all the fundamental first steps that must be taken for a functioning ecosystem to be reconstructed with its full complement of chemical and physical and biological components (Bradshaw 1983). The focus of research on minesoils has generally centered around the characterization of naturally revegetated, unamended minesoils including the characterization of minesoils with different overburden composition, and the characterization of minesoils amended with treatments of inorganic fertilizer, topsoil, and various organic amendments alone or in combination.

Unamended Minesoil Genesis

Surface mined land reclamation, to be successful, depends on detailed knowledge of the physical and chemical properties of the overburden materials to be removed and replaced. Indeed, the mining and reclamation plan and the post-mining land use designation would be of little value without the use of this knowledge to create a reclaimed landscape that meets the objectives of the law and the landowner. Research has documented the physical and chemical limitations of minesoils and how these limitations change over time as a result of the soil-forming factors and with changes in minesoil rock composition. Most of the research on unamended minesoils and spoil materials shows that the natural soil forming factors improve the physical and chemical characteristics of minesoils over relatively short periods of time.

Physical Properties

Minesoils are typically young soils derived from a heterogeneous mixture of sandstone and siltstone fragments in a matrix of loamy material created by the physical breakdown of rock during the mining process (Schafer et al. 1980). In 1- to 29-year-old minesoils in Pennsylvania, Ciolkosz et al. (1985) reported rock fragment contents of 40 to 60 percent in surface horizons and greater than 70 percent in subsurface horizons (total soil weight basis). Rapid physical and chemical weathering caused the percentage of surface rock fragments to be 10 to 30 percent lower than that of subsurface horizons (Ciolkosz et al. 1985, Schafer et al. 1980). In a survey of spoil bank material in eastern Kentucky, Barnhisel and Massey (1969) reported textures in the soil-sized fraction (<2mm) that ranged from loam to clay, and they reported that spoil materials should provide an available water supply adequate to support cover crops under normal weather conditions. Similar results were reported by Plass and Vogel (1973) in a survey of spoil material in southern West Virginia; spoil from 39 surface mine sites showed a mean of 37 percent soil-sized fraction (<2mm) by weight, and available water was judged sufficient for vegetation growth. However, the characterization of available water was not performed on a whole-soil basis and would certainly have been lower due to the lower available water-holding capacity of coarse fragments (Brady 1990). However, the moisture supply, particularly for trees, may be improved over that of shallow, native soils due the increased rooting depth provided by deep minesoils (Sencindiver and Smith 1978).

Available water supply is also affected by traffic pans and surface compaction in minesoils. Detrimental compaction from grading with heavy equipment is a common problem in minesoils (Daniels and Amos 1984; Bradshaw 1983; Sencindiver and Smith 1978). Investigations of a 135-ha, reclaimed surface mine in southwest Virginia revealed that half of 30 minesoil pits had traffic pans occurring less than 70 cm deep with bulk densities of approximately 1.8 g cm^{-3}. Such compaction severely limits root growth and water movement, two important factors contributing to minesoil weathering and development. Where traffic pans were absent, soil genesis occurred quickly with the formation of A horizons 30 cm thick or more in 4- and 5-year-old spoils (Daniels and Amos 1981).

Chemical Properties

Minesoil Reaction

Toxic levels of acidity are commonly associated with minesoils due to the weathering of pyrite in some spoil material (Bradshaw 1983). However, pyritic materials occur infrequently; and, when they do, SMCRA requires that all such toxic materials be buried below the rooting zone. Acid-base accounting is a popular method for predicting the potential acidity of spoil material and for determining whether a material should be buried to avoid toxicity to vegetation (Smith and Sobek 1978, Sencindiver and Smith 1978). The pH of minesoils is most controlled by the parent material from which it was derived. Spoil material that contains pyritic material can have a pH as low as 2 (Daniels and Amos 1981, Barnhisel and Massey 1969), while material containing gray siltstone high in carbonates can have a pH as high as 8 (Daniels and Amos 1984). The occurrence of extremes in pH levels in most spoil material is generally not a widespread problem for vegetation establishment (Czapowskyj 1973). The pH of 68 percent of the samples taken on 39 spoils in southern West Virginia was 5.1 or higher (Plass and Vogel 1973).

A controlled overburden placement study in Wise Co. Virginia, described by Daniels et al. (1983), was designed to study the effects of different mixes of rock type and different organic amendments on minesoil properties. The pH levels of all minesoil rock types containing siltstone fell from 1982 through 1984 presumably due to the acidification reactions of added NH_4 fertilizer and leaching of carbonates and basic cations (Roberts 1988a). All plots received 1120 kg ha^{-1} of 15-13-12.5 N-P-K fertilizer (as NH_4NO_3, $(NH_4)_2HPO_4$, KCl) and yearly additions of 56 kg N ha^{-1} as NH_4NO_3, and the sandstone and siltstone strata had roughly 2.5 percent complex carbonate cements. By 1987, pH levels in all treatments had risen to levels comparable to the 1982 levels (5.5 for sandstone to 7 for pure siltstone) presumably due to the release of carbonates into solution by continued weathering and the slowing of fertilizer-induced acidification (Haering et al. 1993).

Phosphorus

N and P are often the most limiting macronutrients on mined lands. However, for seedling establishment and plant invasion, P can be the more limiting of the two. P fertilization can overcome P deficiencies and provide P for the long-term (Woodmansee et al. 1978). However, many minesoils have a high P-fixing ability, so the efficiency of large, one-time applications should be monitored (Daniels and Amos 1984). P levels in 87 percent of samples taken from 39 spoil materials in southern West Virginia were classified as being low or very low, ratings that mean that these spoils had insufficient levels of P for vegetation establishment and growth (Plass and Vogel 1973).

P values can be overestimated in minesoils high in carbonates when an acid extractant is used. Calcium phosphates (like apatite) are soluble in acid extracts, and their presence would overestimate the plant-available P in minesoils (Daniels and Amos 1984). The $NaHCO_3$ method is effective in acid and calcareous conditions and it primarily extracts anion P on mineral surfaces which would be plant available (Olsen and Sommers 1982, Daniels and Amos 1984). Everett (1981) reported that while the $NaHCO_3$ method correctly predicted a response to P fertilizer, the response varied significantly with rock type making the usefulness of this method for precise fertilizer prescriptions low unless detailed information of rock type is known.

Electrical Conductivity

High levels of soluble salts are often a problem in fresh minesoils due to the exposure of unweathered, newly fractured rock surfaces to the forces of weathering. Daniels and Amos (1984) recommended avoiding the use of materials with saturated electrical conductivities (EC) greater than 0.5 to 0.8 S m^{-1}. Ciolkosz et al. (1985) sampled 24 Pennsylvania minesoils that had no evidence of topsoiling or cultivation. Fourteen of the minesoils had at least one horizon with an EC greater than 0.1 S m^{-1}, while 16 natural soils had no horizons with such conditions. The highest salt concentrations were found below 1 m, and the higher the subsurface salt concentration, the closer to the surface that concentration was found. The high salt concentration in soils of a humid region was attributed to acid sulfate weathering that produced sulfate anions and cations faster than they could be leached from the profile. EC was related more to parent material than minesoil age as many minesoils had EC values of 0.1 to 0.3 S m^{-1} after 2 or 3 years and the highest EC was found on a 7 year old minesoil (Ciolkosz et al. 1985). In the controlled overburden placement study, Roberts et al. (1988) reported that all minesoil mixes containing siltstone had significantly higher EC values than the sandstone minesoil.

Exchangeable Bases

Sweeney (1979) surveyed minesoils from the New River Formation in West Virginia; base saturation in the A horizons of sandstone, shale, and mixed minesoils was higher (36, 29, and 42 percent, respectively) than three natural soils in the area (6 percent average). Roberts et al. (1988a) reported that extractable Ca and Mg increased as siltstone content increased, and that Ca and Mg together made up 85 to 95 percent of all extractable cations. Also in the controlled overburden placement study, reported by Haering et al. (1993), all spoil mixes showed decreases in extractable Ca and Mg from 1982 to 1984 at the same time pH was dropping. By 1987, Ca and Mg levels were higher than 1984 levels, an increase that was attributed to continued weathering of carbonate cements and the cycling of nutrients by grass vegetation after rapid initial leaching losses in surface horizons.

Carbon and Nitrogen

Early minesoil studies (Plass and Vogel 1973, Czapowskyj 1973) recognized nutrient deficiencies, particularly N, but focused primarily on predicting fertilizer responses to these deficiencies. As a result, the role of organic C as a microbial energy source, and the role of organic matter (OM) as an organic N source, has only recently received attention in the form of long-term studies. In a minesoil chronosequence study in southeastern Montana, Schafer et al. (1980) reported that minesoils often had more organic C in the upper 5 cm than did natural soils, but that 400 or more years of C accumulation may be needed to reach the levels of C found at a depth of 20 to 50 cm in natural soils. C accumulation rates were 45 g m^{-2} yr^{-1} in a fifty-year-old minesoil and 135 g m^{-2} yr^{-1} for a six-year-old minesoil due to the rapid initial growth of fertilized, perennial grasses and legumes in the younger minesoil. N accumulation rates were 2.6 and 7.9 g m^{-2} yr^{-1} for old and new minesoils, respectively. Overall, minesoil C/N ratios were 17 to 18 compared to 10 in natural soils (Schafer et al. 1980). Chichester and Hauser (1991) reported similar results on reclaimed, lignite surface mines in east-central Texas. Over 6 years, an unamended minesoil accumulated more total organic C (from 1.6 percent initially to 2.4 percent) than three minesoils amended with topsoil (from 0.3 percent initially to 0.9 percent). The unamended minesoil also accumulated more total N (from 0.05 percent initially to 0.11 percent) than topsoil amended minesoils (from 0.04 percent initially to 0.07 percent) over six years. C/N ratios declined from 33 to about 22 in the surface few centimeters in the unamended minesoil over the same time period (Chichester and Hauser 1991). Daniels and Amos (1981) reported mean OM content of five-year-old minesoils from the Wise Formation on the Powell River Project in Wise County, Virginia. The OM content was 1.4 percent for the A horizons and 0.9 percent for C horizons (n=15). On the same study site, OM content for 12-year-old minesoils was 2.3 percent in the A horizon and 1.2 percent in the C horizon (n=4). These results indicate the ability of a substrate that is initially devoid of organic C and N sources to accumulate pools of C and N relatively quickly by the natural processes of soil formation and plant growth and succession.

Minesoil productivity depends not only on the accumulation of C and N pools but also on the mineralization of these pools by soil organisms to produce plant-available forms of N and other nutrients. Reeder and Berg (1977) studied incubated samples of Cretaceous shale, spoil material, and natural soils in Colorado; mineralization rates of indigenous N, nitrification rates of added NH_4^+, and CO_2 evolution were reported on incubated samples from 0 to 20 cm. The pure shale sample had no net N mineralization; fresh minesoil mineralized 5 mg kg^{-1} NO_3^--N, vegetated minesoil mineralized 49 mg kg^{-1} NO_3^--N, and the natural soil mineralized 75 mg kg^{-1} NO_3^--N. The nitrification ability of 60 mg kg^{-1} added NH_4^+-N in the materials was 0, 36, 100, 117 mg kg^{-1} NO_3^--N for shale, fresh minesoil, vegetated minesoil, and natural soil, respectively. Cumulative evolved CO_2 was lowest for fresh minesoil, while the amounts of evolved CO_2 were similar for the shale, vegetated minesoil and the natural soil. The natural soil had about 65 percent of the total C as was found in the spoil and shale samples that indicated a more available C source in the natural soil. But, the similar CO_2 amounts for the vegetated minesoil and the natural soil indicated that the heterotrophic microbes in minesoils were capable of mineralizing the C that had accumulated in the unamended minesoil (Reeder and Berg 1977).

Li and Daniels (1994) studied 10 minesoils (from 1- to 30-years old) and 1 forest soil on the Powell River Project in southwest Virginia. Results included detailed analysis of the forms of N in minesoils and their accumulations over time. The geologic N found in the minesoils was composed of fixed N and nonhydrolyzable organic N, both of which were stable and unavailable to plants. Active N, that portion of organic N that is mineralizable and available, was low to nonexistent in minesoils. In the forest soil, 81 percent of the total N was in the form of active N; when topsoil is replaced, active N is the main form of N added. The N accumulation rate was 23.4 kg ha^{-1} yr^{-1} in the 0 to 5 cm layer and 3 kg ha^{-1} yr^{-1} in the 5 to 10 cm layer of minesoil; these rates were characterized as low compared to other revegetation systems because a vigorous legume component was not a priority when older sites in the study were revegetated. The N accumulation patterns agree with reported formation of A horizons on these minesoils due to the accumulation of organic matter in the surface horizons (Daniels and Amos 1981). Total N was strongly correlated to C content of the minesoils (r^2=0.96, P<0.001) (Li and Daniels 1994). Active N was strongly correlated with minesoil age (r^2=0.73, P<0.01) in the 0 to 5 cm layer (Li and Daniels 1994).

All of these results show that, even when mined-land reclamation did not involve topsoil or organic amendments, mineralizable forms of C and N accumulated. In most instances, however, the time frame for natural restoration of productive ecosystems on poorly reclaimed land would be unacceptably long from an economic and an environmental standpoint. One of the most important problems in mined-land reclamation concerns making minesoils productive both initially and for the long-term.

Carbon and Nitrogen Cycling: disruptions caused by mining and reclamation alternatives

For the purposes of this discussion, the major N cycle components are the following: N pools found in the litter-root-microbial biomass component, which comprises the fast-cycling pool of organic C and N; the soil organic matter (SOM) component, which comprises the slow-cycling pool of C and N in stable humus; and the mineral N component, which is the active pool of inorganic N. The important fluxes are the fast-cycling path of mineralization of the litter-root-microbial biomass component and the slow-cycling path of mineralization of the SOM component (Figure 1). Due to the intimate relationship between the C and N cycles, both will be discussed in the following sections. The inputs and outputs of N associated with the atmosphere, geologic N, fixed N, leaching, NH_3 volatilization, and denitrification, for purposes of this discussion, are assumed to be negligible and/or consistent across relative comparisons. In fresh, unamended minesoils, as was discussed in the previous section, the ability to supply plant-available N is low and often deficient (Bradshaw et al. 1982). This N deficiency does not usually inhibit initial seedling establishment but does limit the long-term productivity of minesoils (Woodmansee et al. 1978, Reeder and Sabey 1987). Despite initial fertilization efforts, plant communities often fail to persist on N deficient sites (Bradshaw 1983). Sparse vegetation due to the failure of plant communities and/or low productivity prevents vegetation from controlling erosion (Woodmansee et al. 1978), may delay bond release and cause further reclamation costs for the coal operator, and prevents the landowner from fully realizing the post-mining land use.

The initial N deficiency is caused by a disruption of the N mineralization cycle which provides a constant N supply that, in an aggrading hardwood ecosystem, is proportional to

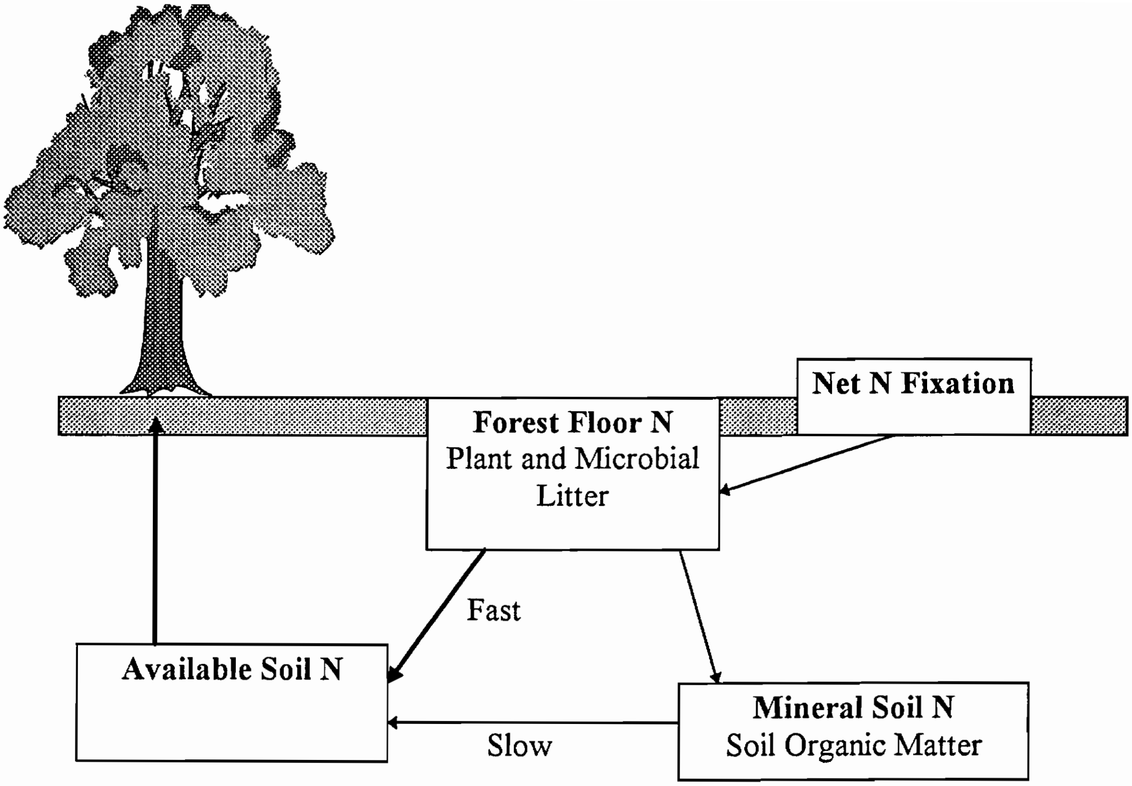

Figure 1. Diagram showing major processes involved in N cycling in a forest ecosystem. The boxes indicate components and the arrows indicate interconnected processes. (After: Woodmansee et al. 1978, Bormann et al. 1977)

the N demand (Bradshaw et al. 1982, Bormann et al. 1977). Mining disrupts the N cycle by altering the forms and amounts of N in the components of the ecosystem and by disrupting the microbial population responsible for N mineralization (Reeder and Sabey 1987).

During the mining and reclamation process, the entire living plant biomass is removed; this eliminates the root-turnover component and the annual inputs to the litter layer. The intact litter layer is also removed, eliminating inputs from this component. The microbial population is largely or completely destroyed; this eliminates the microbial biomass component as well as the mineralization capacity provided by microbes (Reeder and Sabey 1987). Initially, then, mining eliminates the structure and function of both the fast and slow components of the N cycle. To restore the N cycle, N must be supplied to support the initial vegetation in the short-term, and to build the N capital necessary for the N cycle to regain the capacity to supply N for the long-term needs of the ecosystem (Bradshaw et al. 1982). The important questions for reclamation scientists concern the amount of N capital needed to establish a self-sustaining ecosystem, and the most efficient way to achieve this N accumulation (Bradshaw et al. 1982). Decades of work on the reclamation of china-clay wastes in England have led to the conclusion that at least 700 kg N ha^{-1} in the mineral soil was needed for a *Salix* shrub community to become established through natural succession on unamended wastes, and that 1200 kg N ha^{-1} was necessary before mature woodlands become established (Dancer et al. 1977a, Marrs et al. 1981, Roberts et al. 1981). It was also reported that at least 50 years was required for 1000 kg N ha^{-1} to accumulate naturally on unamended china-clay wastes (Bradshaw et al. 1982). The natural accumulation of N can be augmented in three basic ways; the addition of stored organic N through topsoil replacement or organic matter additions, inorganic N fertilization, or the planting of N_2-fixing species (Reeder and Sabey 1987, Bradshaw et al. 1982).

Topsoil replacement and organic matter additions

A topsoil amendment ideally adds plant and microbial residue that contributes to the fast-cycle inputs, and it adds a microbial population to mineralize that fast-cycling organic matter (Woodmansee et al. 1978). Alderdice et al. (1981) measured vegetation response and total N on a Kentucky mine spoil with 13 treatments, a control and 12 treatments of various rates of topsoil, bark, leaves, chicken manure, and sewage sludge. There were no significant differences between the unamended control and the 12 amended treatments after three years for total above-ground biomass of grasses and legumes or for available N (Alderdice and Graves 1983). McGinnies and Nicholas (1980) compared the productivity of winter wheat *(Triticum aestivum*) and wheatgrass (*Agropyron intermedium*) on Colorado spoils amended with different thicknesses of topsoil material. Total herbage production and root production increased linearly with increasing topsoil thickness. Low root production in the spoil material below the added topsoil was attributed to low levels of N and P in the spoil material (McGinnies and Nichols 1980). Roberts et al. (1988b) reported the effects of different cultural amendments on minesoils in Wise County, Virginia; treatments included a control, 30 cm of topsoil (mixed A, E, B and C horizons), 112 Mg ha^{-1} of sawdust, and 4 sewage sludge rates. All plots were mulched with straw and hydro-seeded with KY-31 tall fescue (*Festuca arundinacea*) and paper-fiber mulch. Only the control and the two lowest sludge rate treatments showed significant increases in OM over the two-year period following plot establishment. The OM increases were equivalent to rates of about 700 kg C ha^{-1} yr^{-1} for the control and 1500 kg C ha^{-1} yr^{-1} for the two sludge treatments. Schafer et al. (1980) reported a C accumulation rate of 1350 kg C ha^{-1} yr^{-1} from 0 to 10 years on a topsoiled, fertilized, and seeded minesoil in Montana. This was compared to a C accumulation rate of 450 kg C ha^{-1} yr^{-1} on a 51-year-old, unamended, naturally-revegetated minesoil (Schafer et al. 1980). Roberts et al. (1981) reported 1134 kg C ha^{-1} yr^{-1} accumulated on china-clay wastes in England from 16 to 116-years-old.

Roberts et al. (1988b) reported N accumulation rates of 21 to 150 kg N ha^{-1} yr^{-1} with accumulation rates highest in the sludge amended minesoil and lowest in the sawdust amended minesoil. Schafer et al. (1980) reported N accumulation rates of 26 to 79 kg N ha^{-1} yr^{-1} on old and new minesoils, respectively. Roberts et al. (1981) reported a N accumulation rate of 10.3 kg N ha^{-1} yr^{-1} on china-clay wastes. Initial C/N ratios in the controlled overburden placement study were 9 to 10 in the control and sludge treatments, 16 in the topsoil, and 24 in the sawdust treatment; after two years, only the topsoil ratio had decreased (from 16 to 14) all other treatment C/N ratios increased (Roberts et al.

1988b). A widening of C/N ratios as both C and N are accumulating indicates that N accumulated slower than C accumulated; this could precipitate a N deficiency due to the lack of further N additions that could be supplied by a recovering N cycle. Indeed, total standing biomass of fescue, on the controlled overburden placement study, declined an average of 61 percent across all treatments by the third growing season (Roberts et al. 1988b).

Results on the first three years of a lysimeter study were reported by Schoenholtz (1990, 1992) and will be discussed in detail in later sections of this work. Lysimeters were used in a factorial design to determine the effects of topsoil replacement, whole-tree woodchips amendments, and N fertilization on minesoil properties and on ground cover and tree productivity. In the wood chip treatment, total N, mineralizable N, and organic C were 10, 50, and 18 percent higher, respectively, than the control after the third year. The wood chips treatment had over twice the tree volume than either topsoil or control treatments after the second year; this was largely attributed to a mulching effect which created better moisture conditions during dry, summer months. The topsoil treatment increased total N and mineralizable N by 23 and 46 percent over the control, but there was no topsoil effect on tree volume or total ground cover percent (Schoenholtz 1992).

Some common problems associated with topsoil replacement are as follows: the topsoil may not be of sufficient depth or quality; SOM formation in topsoil-amended minesoil may act as a N sink for decades or centuries until a new equilibrium is reached; storage of topsoil causes a loss of aggregation; there may be considerable conversion of organic N to NO_3^- which readily leaches out of the pile; populations of fungal species change as storage time increases; the innoculum potential of vesicular-arbuscular mycorrhizae (VAM) decreases as storage time increases (Reeder and Sabey 1987).

Fertilization

N fertilization on mined lands with inadequate topsoil usually results in better yields initially (Bradshaw 1983); however, the effect is short-lived without continued fertilizer applications (Woodmansee et al. 1978). Ideally, N fertilization adds inorganic N bypassing the OM decomposition and mineralization components of the N cycle until these components are established. Problems with N fertilization include the following: fertilization at seedling establishment can promote weed competition at the expense of desired species; multiple applications are expensive, and large, one-time applications are poorly utilized; fertilization benefits are short-term and are often insufficient to meet the N needs until adequate cycling has been established; and there are often large leaching losses of N fertilizer (Reeder and Sabey 1987).

Dancer (1975) studied the effects of fertilizer applications to sand wastes from kaolin mining; more than 98 percent of fertilizer-NO_3^- applied to uncultivated, sand wastes was leached from the 0 to 20 cm layer with one month of average rainfall. It was concluded that the use of inorganic fertilizer salts at the time of seeding for the reclamation of coarse-textured spoils is wasteful and of questionable value (Dancer 1975). In a comparison of topsoil and minesoils in Colorado and Wyoming, Reeder (1988) reported that more NH_4^+ was nitrified in minesoils than in topsoil, and that 40 to 50 percent of added N fertilization may be susceptible to leaching.

Lysimeter studies provide definitive information on the leaching of nutrients from ecosystems. Marrs and Bradshaw (1980) used lysimeters to monitor leaching losses of applied nutrients from china-clay wastes. Seventeen percent of applied N was lost via leaching from lysimeters where fertilization and seeding were simultaneous; only 5 percent of applied N was lost from already vegetated spoil. However, P, Ca, and Mg losses were 65, 77, and 72 percent respectively from the vegetated wastes (Marrs and Bradshaw 1980). These losses are problematic given that low pH levels and low amounts of Ca and P severely reduce the N-fixing capacity of most forage legumes (Tisdale et al. 1993).

Schoenholtz (1990) reported that lysimeter tanks of minesoil receiving 100 kg N ha^{-1} lost 53.7 kg N ha^{-1} compared to 6.1 kg N ha^{-1} in the control during the first year. After the second year, losses had dropped to 0.84 and 0.71 kg N ha^{-1} for the fertilized and unfertilized lysimeters respectively; there were no significant differences in leaching losses between amendment treatments.

Legumes

The role of legumes in natural succession has long been understood; colonization by N_2-fixing species provides the N accumulation necessary for later successional, non-N_2-fixing species to colonize that site and grow (Crocker and Major 1955, Lawrence et al. 1967). Often, it is not until a certain critical level of total soil N has been reached that non-leguminous, woody vegetation can achieve and maintain dominance (Crocker and Major 1955, Lawrence et al. 1967, Bradshaw et al. 1982). The presence of an aggrading ecosystem, like a hardwood forest in the temperate east, represents the achievement of one of the goals of mined-land reclamation, namely long-term sustainability, due to their "closed" nutrient cycles (Bormann et al. 1977, Vitousek and Reiners 1975). Given the ephemeral nature of fertilizer N and the uncertain quality of and high costs associated with topsoil and organic amendments, legumes provide an attractive alternative for accumulating organically bound N, the mineralization of which is critical to meet the long-term N demand of a developing ecosystem (Bradshaw 1983).

In a study of natural communities on kaolin wastes, Dancer et al. (1977a) reported that three, legume-dominated sites had 82, 63 and 124 kg N ha^{-1} yr^{-1} net accumulation rates in the surface 27 cm. Palaniappan et al. (1979) reported that a *Lupinus arboreus* stand on china-clay waste accumulated N at a rate of 185 kg N ha^{-1} yr^{-1} for its short life span of around six years. At this rate, roughly five years would be needed to accumulate the reported 700 to 1000 kg N ha^{-1} necessary for a self-sustaining, shrub ecosystem to become established (Dancer et al. 1977a). In a species trial of 22 legumes on sand wastes and colliery spoil, Jefferies et al. (1981a) reported maximum N accumulation rates of 295 kg N ha^{-1} yr^{-1} with 76 kg N ha^{-1} being transferred to a grass companion crop. Forage legumes were recognized as more intolerant of Ca and P deficient sites than woody legumes (Jefferies et al. 1981a). Dancer et al. (1977b) studied forage legumes on sand and mica wastes. The net N-fixation rate for *Trifolium pratense* was 281 kg N ha^{-1} yr^{-1} and was 210 kg N ha^{-1} yr^{-1} for *Lotus corniculatus*, values were 151 and 117 kg N ha^{-1} yr^{-1}, respectively when grown on sand wastes. Results of this study indicate that forage legumes can accumulate 700 kg N ha^{-1} in three to four years on mica wastes (Dancer et al. 1977b). In another transfer study, Jefferies et al. (1981b) reported that when bent grass and white clover were grown together, bentgrass had 85 kg N ha^{-1} in shoot biomass compared to 6 kg N ha^{-1} in the control treatment and had a yield five times greater than the control treatment. Schoenholtz (1990) reported first-year, N-fixation values of 195 kg N ha^{-1} for the fertilized treatment and 57 kg N ha^{-1} for the unfertilized treatment; there were no significant differences, however, in the second and third years. Third year net fixation rates were 263, 240, and 136 kg N ha^{-1} yr^{-1} for the control, topsoil, and woodchip treatments respectively.

Problems with legumes include the following: the use of legumes may not be allowed due to native species requirements by the reclamation authority, legumes are not well suited to dry, saline, or sodic conditions, and legumes can dominate a site and reduce diversity (Reeder and Sabey 1987).

Reclamation researchers and practitioners have gained a great deal of knowledge about the physical and chemical characteristics of spoil materials, how they change over time and how they change under the influence of different cultural treatments. However, mine-related research has often focused on the effects of topsoil or organic amendments on C and N accumulation and cycling in minesoils while giving less attention to the "natural" and often comparable accumulation of C and N that may have occurred in the unamended control treatments. The implied assumption being that unamended minesoils, particularly topsoil substitutes, required organic or inorganic amendments to be productive. Research has shown that this is often the case when the ground cover of interest is a forage crop, like tall fescue, that has a high, initial demand for nutrients. Absent this high, initial demand, three factors point to the possibility for making topsoil substitutes into productive minesoils capable of supporting trees. First, an aggrading forest ecosystem has a low initial demand for nutrients, particularly N. Second, much of the literature has shown that Appalachian mine spoils generally have good physical properties and low toxicities. And third, herbaceous legumes, available for reclamation ground cover, can contribute significant amounts of N to minesoils. A detailed analysis became necessary to test if the prescription for reclamation forestry was productive and sustainable. Research was needed on the long-term accumulation of OM and the cycling of nutrients that occurs in topsoil substitutes reclaimed using different methods aimed at reestablishing the complex cycling of nutrients found in mature ecosystems.

As revealed by the literature, much of the mine-related research has involved the use of chronosequence studies; there are very few designed experiments that have both the strict controls necessary for definitive results and the operational scale necessary for relevant problem solving. This lysimeter study, started in 1987, provided results for relevant problems, such as the restoration of C and N cycles in topsoil substitutes, and did so over a time frame long enough to allow for more informed, long-term predictions of forest ecosystem sustainability.

METHODS AND MATERIALS

Project Design

This project was initiated at the Reynolds Homestead Forest Resources Research Center in Critz, Virginia, in 1987 and was fully described by Schoenholtz (1990). Large concrete lysimeters were used as experimental units in a 2 by 3 factorial experiment testing the effects of two levels of N fertilization and three levels of organic amendment on C and N cycling in minesoil. Each treatment combination was replicated three times. Data on all the inputs and outputs for each lysimeter allowed a complete C and N mass balance analysis to be performed for the first three years of the project. The data necessary to continue the mass balance analysis was not collected in the intervening years; however, it was still possible to study changes in C and N cycles over 8 years.

In July, 1987, eighteen concrete lysimeters were filled with a pre-weighed amount of fresh mine spoil associated with the Middle Wise Formation. The mine spoil consisted mainly of sandstone and siltstone with traces of shale present. An attempt was made to fill each lysimeter with the same percentage of the different size fragments present in minesoils ranging from sand-sized particles to large rocks. Each lysimeter has a surface area of 2.9 m^2 and a depth of 0.8 m; a 12.7 mm perforated PVC pipe was placed on the floor of each lysimeter and covered with 3 cm of quartz gravel. Pipes were connected to a drainage system that allowed leachate to be collected and analyzed.

Six of the lysimeters received 5 cm of topsoil found in the area where the spoil was removed. The topsoil consisted of the A horizon from a Jefferson series soil (loamy, mixed, mesic typic Hapludult) found in Wise County, Virginia. Six lysimeters received 8 cm of fresh yellow-poplar (*Liriodendron tulipifera* L.) whole-tree chips, and the remaining six lysimeters received no organic amendments (Table 1). Within the three treatments, half received 100 kg ha^{-1} N applied as NH_4NO_3 and half got no N fertilization. All lysimeters received 100 kg ha^{-1} phosphorus and 60 kg ha^{-1} potassium in July, 1987. The wood chips had a C/N ratio of 261:1 and were used to provide a source of organic N and a carbon source for heterotrophic bacteria. The topsoil had a C/N ratio of 17:1 and was used to evaluate the potential of topsoil as a source of organic N and as a microbial innoculum to promote N cycling (Table 1). The wood chips and topsoil were tilled into the top 25 cm of the mine spoil prior to seeding and tree planting.

In July 1987, a tree-compatible mixture of the following grass and legume species was sown in each lysimeter: foxtail millet [*Setaria italica* (L.) Beauv.], perennial ryegrass

Table 1. Selected properties of the organic amendments prior to mixing with the minesoil.[1]

Property	Amendment	
	Woodchips	Topsoil
Organic C (g kg^{-1}) †	470.6	33.5
Total N (g kg^{-1}) ‡	1.78	2.02
C/N	261:1	17:1
Dry weight added (Mg ha^{-1})	50	500
Organic C added (Mg h^{-1})	23.5	16.75
Total N added (Mg h^{-1})	0.09	1.00
P (mg kg^{-1})	97.8§	22.2¤
Cations (mg kg^{-1})		
K	558	153#
Ca	1745	1069
Mg	393	144
pH ††	-	5.5
Electrical conductivity (S m^{-1}) ‡‡	-	0.011
Fine-soil particle size analysis (%)		
Sand	-	65
Silt	-	25
Clay	-	10

[1] Schoenholtz (1992)

† Dry combustion

‡ Micro-Kjeldahl digestion

§ P and cations by dry ash and 6 M HCl extraction

¤ 0.5 M $NaHCO_3$ extraction

Cations by 1 M NH_4OAc extraction

†† 1:2 soil/water slurry

‡‡ 1:5 soil water slurry

(*Lolium perenne* L.), annual ryegrass (*Lolium multiflorum* Lam.), redtop (*Agrostis gigantea* Roth), birdsfoot trefoil (*Lotus corniculatus* L. var. *corniculatus*), Korean lespedeza (*Lespedeza stipulacea* Maxim.), and 'Appalow' sericea lespedeza [*Lespedeza cuneata* (Dum.-Cours.) G. Don]. Ten 1-0 bareroot pitch *x* loblolly hybrid pine (*Pinus rigida* L. *x P. taeda* L.) seedlings were planted in each lysimeter in March 1988. The legumes accounted for over 80 percent of the ground cover after three years, and tree survival was 60 percent in the topsoil treatment, 83 percent in the control, and 98 percent in the woodchip treatment (Schoenholtz 1992).

Field and Laboratory Methods

Above Ground Biomass Analyses

Survival, height, and ground-line diameter of all trees were recorded on a yearly basis from 1987 through 1994. These data served as a bioassay of treatment effects.

The foliar nutrient status of the pitch *x* loblolly pine trees was used to determine if there were treatment effects on tree nutrient status. Foliage samples were collected from all trees in each lysimeter during the winter months. Samples were taken from the last full flush of growth, from the top third of the tree, and from the side of the tree facing the same direction. Foliage was dried at 65°C prior to analysis. The average weight of a subsample of 100 fascicles was determined per treatment. The samples were ground and a subsample from the composite was used to determine foliar N content using the method outlined by Bremner and Mulvaney (1982). P, K, Ca, and Mg content were also determined using ICP spectrometry on samples dry-ashed at 500°C and extracted with 6 M HCl.

By 1994, there were 8 to 10 trees, each approximately 2 m tall, in most of the lysimeters; trees had become pot-bound and often suffered from moisture stress. In addition, some lysimeters had 5 trees or less, and two lysimeters had only one tree. Tree volume and nutrient analysis data were discussed in light of all of these factors, and were presented only to characterize the status of the above-ground system.

Soil Analyses

For the following chemical analyses, soil samples were collected from the 0 to 10 cm layer in each lysimeter. A 2-cm diameter push tube was used to collect 20 to 30 randomly located samples that were composited. This sample collection method and the following analytical methods were the same used by Schoenholtz (1990) and were repeated to allow for the direct comparison of data over time.

Minesoil characterization methods

From the 0-10 cm composite soil sample from each lysimeter, the following chemical analysis methods were conducted:

- Available phosphorus was determined by extraction with 0.5 M $NaHCO_3$ adjusted to pH 8.5 (Olsen and Sommers 1982).
- A particle size analysis was conducted using the hydrometer method (Gee and Bauder 1986).
- Bulk density was determined by the balloon excavation method (Blake and Hartge 1986).
- pH was determined in the supernatant of a 1:2 soil/water slurry with a pH electrode (McClean 1982).
- Electrical conductivity was determined with a conductivity cell in a 1:5 soil/water slurry and referenced to a standard 0.01 M KCl solution (Rhoades 1982).

C and N methods

The change in TKN was used as the test criterion for the first null hypothesis that N accumulation in an unamended topsoil substitute was not significantly different from the N accumulation in minesoils amended with topsoil or organic matter.

- Total Kjeldahl nitrogen (TKN) was determined by a modified micro-Kjeldahl digestion procedure (Bremmer and Mulvaney 1982) and was used to measure N accumulation.

Results for N mineralization were used to test the second null hypothesis that N availability in an unamended topsoil substitute is not significantly different from the N availability in minesoils amended with topsoil or organic matter. Changes in these parameters over time were also evaluated. N mineralization was determined using three methods.

- N mineralization potential (N_o) was estimated from composite samples using the aerobic incubation procedure of Stanford and Smith (1972) as modified by Burger and Pritchett (1984). Three replicate cores from each lysimeter (containing a mixture of roughly 70 g soil and 200 g quartz sand) were incubated at 32°C for 22 weeks. Accumulated inorganic N was leached with 0.01 M $CaCl_2$, and the leachate was analyzed for NH_4^+ and NO_3^- colorimetrically using a Technicon Autoanalyzer II (Technicon Industrial Systems 1973a and 1973b). Cumulative N mineralization (N_t) data were fit to a first-order equation using non-linear, least-squares regression (NLLSR) to determine N_o and the rate constant (k).

$$N_t = N_o(1-e^{-kt}) \quad [1]$$

- Anaerobically mineralized ammonium (An-N) was determined by the procedure described by Keeney (1982). NH_4^+ was determined colorimetrically using a Technicon Autoanalyzer II.
- An in-situ buried bag incubation was used to determine net N mineralization. A soil sample was divided, and one half was returned to the lab for immediate analysis and one half was placed in a polyethylene bag and buried roughly 5 cm. Two bags per

lysimeter were treated as subsamples. Buried bags were removed after one month. Following extraction with 2 M KCl, NH_4^+-N and NO_3^--N concentrations were determined colorimetrically using a Technicon Autoanalyzer II. Net N mineralization was calculated as the difference in extractable N between unincubated and field-incubated samples.

N_o is an estimate of the amount of the total mineralizable N found in the system of interest, this was compared to TKN to provide a N turnover index (N_o/TKN). While TKN provides data on the N capital, the N turnover index provided data on the quality of the N pool relative to mineralization.

Results on C accumulation and mineralization were used as the test criteria for the third hypothesis that the amount of carbon accumulated and mineralized in an unamended topsoil substitute is not different than the amount of carbon accumulated and mineralized in minesoils amended with topsoil or organic matter and does not affect the ability of a minesoil to mineralize nitrogen.

- Total organic carbon (TOC) was determined by dry combustion (Nelson and Sommers 1982) and was used to measure C accumulation.

C mineralization was determined by two methods:

- In-situ CO_2 evolution was measured using the procedure outlined by Anderson (1982). Plastic containers, with a surface area of 242 cm^2, were placed over the soil surface;

litter was not removed. 1 M NaOH was used to trap CO_2 for 24 hours; the solutions were titrated with a standardized 0.2 N HCl to determine absorbed CO_2.

- The C mineralization potential (C_o) was determined using an incubation procedure similar to that described by Burger and Pritchett (1984). Composite soil samples from two locations in each lysimeter were used to construct two cores per tank. Cores were incubated at 33°C for 10 weeks. During that time, cores were replenished with a N-plus solution and monitored for CO_2 evolution; in this way the cores provided an estimate of C mineralization potential that was not affected by differences in initial N content. CO_2 measurements were conducted weekly using an infrared gas analyzer connected to a PVC cap that fit over the cores. Evolved CO_2 data were adjusted for the weight of soil in each core and converted to mg C per 100 g oven-dry soil. NLLSR was used to fit cumulative evolved C (C_t) to a first-order equation of the form:

  $$C_t = C_o(1-e^{-kt}) \qquad [2]$$

  where C_t is cumulative evolved C, C_o is the C mineralization potential, k is the rate constant, and t is time. C_o was compared to TOC as an index of the quality of the organic matter present in the minesoil.

Results from the first three years of this experiment showed that the fertilizer treatment effects on N and C parameters ceased to be important after the first year. Results from the above C and N methods were used to test for fertilizer treatment effects and none were found.

Statistical Design and Data Analysis

The study was a 2 by 3 factorial in a completely randomized design with three organic amendments (control, topsoil, and wood chips) and two levels of inorganic N fertilizer (control and 100 kg ha^{-1}). The six treatment combinations were replicated three times. See Appendix A for a list of treatment combinations and the assignment to lysimeters. Due to the transitory nature of the N fertilizer applied in 1987, by 1989 there were no significant differences between N fertilizer treatment effects on vegetation and soil variables. Therefore, data analysis for this project used a one-factor analysis of variance with three levels (control, topsoil, and wood chips) and six replications per level followed by Duncan's Multiple Range Test to test the differences among treatment means ($\alpha = 0.05$). Non-linear, least-squares regression (NLLSR) was used to estimate N_0 from aerobic incubation data and C_o from the C mineralization incubation data. NLLSR was also used to determine the accumulation rates (k) of TOC and TKN. All data analysis was done using SAS statistical software (SAS Institute Inc. Cary NC).

RESULTS AND DISCUSSION

The Effects of Organic Amendments on the Physical Properties of an Appalachian Minesoil

Particle Size

The coarse-fragment fraction of most minesoils weathers quickly (Ciolkosz et al. 1985, Schafer et al. 1980). Sandstone fragments break apart faster than siltstone fragments due to the mechanical forces of overburden handling and subsequent physical and chemical weathering (Torbert et al. 1988, Daniels and Amos 1985). From 1989 to 1995, there was an average 19, 24, and 25 percent reduction in coarse fragment content by weight for the control, topsoil, and woodchip treatments, respectively (Table 2). The decline in coarse fragment content, from 1989 to 1995, was significant ($P<0.0001$) for all three treatments. In a study of minesoil mixes ranging from pure sandstone to pure siltstone, Haering et al. (1993) reported a decline in coarse-fragment content from 65 to 55 percent over five years in pure sandstone plots with no significant difference over time in the coarse-fragment content of siltstone mixes. The spoil material used in this research and for the research

Table 2. Effect of organic amendments on the physical properties of an Appalachian minesoil (from 0 to 25 cm.) after 2 years and after 8 years.[1]

Treatment	Coarse Fragment Content	Particle Size Analysis			Bulk Density	
		Sand	Silt	Clay	Whole-soil	Fine-soil (<2 mm.)
	%				g/cm^3	
1989						
Control	64c[2]	69b	15ab	16a	1.76a	1.09a
Topsoil	68b	68b	16a	16a	1.58b	0.84b
Woodchips	75a	73a	13b	14b	1.40c	0.58c
1995						
Control	52a	63b	24a	14a	1.82a	1.46a
Topsoil	52a	61b	26a	13a	1.78ab	1.42a
Woodchips	56a	66a	22b	13a	1.72b	1.33a

[1] Values are means of 6 replications.

[2] For each date, means within columns with different letters are significantly different at the 0.05 level.

reported by Haering et al. (1993), for a controlled overburden placement study, both came from the Powell River Project area in Wise County, Virginia. These results, and those reported by Haering et al. (1993), show that minesoils with high sandstone content can weather quickly during the course of five to eight years.

In conjunction with the rapid weathering of coarse fragments, there was an average 10 percent reduction in sand-sized particles and an average 63 percent increase in the silt-sized particles for the three treatments over the same 6 year period (Table 2). The woodchip treatment retained a slight but significantly higher sand content and a lower silt content than either the topsoil or control treatments. These differences were not attributed to the effects of organic amendments but were probably due to small differences in initial mine spoil composition. Aside from this, there were no significant differences in particle size distribution among the three treatments after 6 years (Table 2). All three treatments showed a small decline in clay content over time; this could be due to the movement of some clay below the 25-cm sampling depth. Ciolkosz et al. (1985) found clay films in the subsoils of Pennsylvania minesoils. Though most clay films were found in minesoils greater than 15 years old, a 5 and a 4-year-old minesoil had clay films described in either the AC, B, or C horizons, evidence that clays can be weathered from surface horizons relatively quickly in skeletal minesoils.

Haering et al. (1993), in the controlled overburden placement study, reported no significant change in particle-size after five years in minesoils of pure sandstone, while the minesoils mixed with siltstone decreased in sand content and increased in silt content. These data and the coarse-fragment data from this study suggest that while sandstone coarse fragments may break down quicker than siltstone coarse fragments, the siltstone component is largely responsible for the accumulation of fine-soil material over the short term.

Bulk Density

From 1989 to 1995, both whole-soil and fine-soil bulk density increased in all three treatments (Table 2). Differences among treatments in both categories were smaller in 1995, with no significant differences among treatments in fine-soil bulk density after 8 years (Table 2). The fine-soil bulk density increased more than the whole-soil bulk density after 6 years; this corresponds to the increase in the fine-soil content in all treatments and the settling of the spoil material placed in the lysimeters. The larger increase in fine-soil bulk density in the topsoil and woodchip treatments compared to the control (70 and 130 percent versus 34 percent) was probably due to the additional settling of the organic amendments, as particle-size distributions did not reveal important differences (Table 2).

The bulk densities measured after eight years are high relative to natural soils and are close to values reported as root-restricting (Torbert et al. 1988). However, over several rotations, organic matter will build in the soil, silt and clay-sized particles will increase and bulk density should decrease. In Montana, Schafer et al. (1980) compared minesoils of different ages with a natural soil. In general, the younger minesoils had higher bulk densities than the older minesoils or the natural soil; a difference that was attributed to different overburden placement methods and a higher sand content in the young minesoils. Torbert et al. (1988) examined minesoils, roughly 20 years old, from 34 bench sites in southwest Virginia where the minesoil for this study was also obtained. The average, whole-soil bulk density was 1.04 g cm^{-3} for the 0 to 10 cm layer. The average, whole-soil bulk density for the three treatments in this study was 1.77 g cm^{-3} for the 0 to 25 cm layer (Table 2). Some of this difference in bulk density can be attributed to the higher coarse-fragment content in the minesoils of this study due to the deeper sampling depth; average coarse-fragment content was 53 percent in this study and was 46 percent for the bench site minesoils (Torbert et al. 1988). However, average sand content was 63 percent in this study compared to 56 percent in the bench site study, indicating that changes in particle size distribution over time may lead to a lower bulk density.

The Effect of Organic Amendments on Chemical Properties of an Appalachian Minesoil

Minesoil pH and Electrical Conductivity

The ability of minesoils to support a healthy and productive forest is influenced by pH and total salt (EC) levels (Daniels and Amos 1985, Torbert et al. 1988). Minesoils often have pH levels that are much higher than the pH levels found in native soils of the area (Bradshaw 1983). In addition, minesoils are often composed of unweathered material and freshly exposed surfaces, causing high levels of soluble salts that adversely affect plant growth (Woodmansee et al. 1978). In a survey of 34 mine sites, Torbert et al. (1988) found that of 14 minesoil properties tested, only EC was significantly correlated ($r = -0.43$; $p=0.009$) with the height of eastern white pine (*Pinus strobus*) trees.

At the time this study was initiated, pH levels were significantly higher in the control and woodchip treatments than in the topsoil treatment (Table 3). The pH of the topsoil amendment itself was 5.5 which contributed to the lower initial pH in the topsoil treatment. Over 8 years, decomposition of the pine litter and weathering of carbonates from the surface horizons likely contributed to the decline in pH exhibited by all three treatments (Table 3). The pH levels at year 8 were well within the range of pH values reported for similar experiments (Haering et al. 1993, Moss et al. 1989).

The EC of the minesoils in this study were low (0.04 dS m^{-1} for the control, topsoil, and woodchip treatments) from the outset compared to the work of others (Table 3). Moss et al. (1989) reported third year EC values of 0.60, 0.53, and 0.73 dS m^{-1} for a control, topsoil, and sawdust amended treatments, respectively. Torbert et al. (1988) reported a mean EC of 0.89 dS m^{-1} with a standard deviation of 0.34 dS m^{-1} for 34 reclaimed mine

Table 3. Effect of organic amendments on selected chemical properties in an Appalachian minesoil (0 to 10 cm) after initial addition of amendments (July 1987), after 2 years (October 1989), and after 8 years (March 1995).[1]

Treatment	Available P	pH	EC
	—mg/kg—		—dS/m—
	July 1987		
Control	2.70a[2]	7.4a	0.12a
Topsoil	3.64a	6.8b	0.11a
Woodchips	1.90a	7.3a	0.11a
	October 1989		
Control	5.82a	7.3a	0.04a
Topsoil	6.72a	6.9c	0.05a
Woodchips	6.90a	7.0b	0.04a
	March 1995		
Control	4.58b	6.2ab	0.04a
Topsoil	5.58ab	6.2a	0.04a
Woodchips	6.33a	6.0b	0.04a

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[1] Values are means of six replications.

[2] For each date, means within columns with different letters are significantly different at the 0.05 level.

sites in southwest Virginia. Second year results from the controlled overburden placement study showed an EC value of 0.14 dS m^{-1} in the pure sandstone minesoil and values of 0.23 to 0.25 dS m^{-1} in the mixed sandstone/siltstone minesoils (Roberts et al. 1988b). Spoil material for this research and the controlled overburden placement study came from the Powell River Project area which explains the similarity in EC results. The weathering of carbonates from the surface horizons, which contributed to the decline in pH, may also have contributed to the decline in EC shown over 8 years (Table 3). Daniels and Amos (1984) recommended that spoils with saturated conductivities of 5 to 8 dS m^{-1} be removed to avoid a problem with high soluble salts.

Soil Phosphorus

The problem of P deficiencies and high P fixation in minesoils is well documented (Czapowskyj 1973; Daniels and Amos 1985; Plass and Vogel 1973). Because P is relatively immobile in soils, large, one-time applications of P are often used in agriculture, forestry, and mined-land reclamation to overcome P deficiencies. For this research, 100 kg P ha^{-1} were applied to all tanks at the beginning of the experiment; the July 1987 extractable soil P levels indicate the P concentration in the treatments prior to fertilization (Table 3). Dilute, double-acid extraction methods for determining extractable soil P may overestimate plant available P due to the dissolution of carbonates (Daniels and Amos 1982). For this reason, a $NaHCO_3$ extraction was used to determine plant available P. The extractable soil P levels had risen from the 1987 levels by 1989 and were not significantly different after two years (Table 3). By 1995, soil P levels had dropped in all three treatments with the smallest decline in the woodchip treatment, which was significantly higher than the control. This relatively small decline in the woodchip treatment was probably due to the additional organic P added in the woodchip amendment. Minesoil research has yet to determine a definitive critical level for soil P, but comparisons with other minesoil data show that the soil P levels measured in this study may have always been low. In a survey of 34 minesoils from pre-SMCRA benchsites in southwest Virginia, Torbert et al. (1988) reported a mean soil P level ($NaHCO_3$ extraction) of 10.2 mg P kg^{-1} with a standard deviation of 7.1 mg P kg^{-1} and a range of .2 to 28.5 mg P kg^{-1}. The soil P levels of many of these unfertilized minesoils were higher than the soil P levels in the lysimeters. Moss et al. (1989) reported soil P levels ($NaHCO_3$ extraction) of 22.1, 13.1, and 16.9 mg P kg^{-1} in a control, topsoil, and sawdust amended treatments of a 3-year-old experiment of organic treatments on minesoils in which all treatments had received 147 kg P ha^{-1}. All plots had received herbicide before tree planting, and three-year-old pitch x loblolly pine hybrids had foliar P concentrations above the 0.1 percent P critical level (Allen 1987). Foliar P concentrations of the trees in all treatments had dropped below the critical level by year 8 (Table 4). Bengtson and Mays (1978) reported on six years of loblolly pine growth and nutrition on sandstone-derived minesoils in northeastern Alabama in an experiment with N, P, and ground cover treatments. All treatments received 84 kg N ha^{-1} and 150 kg P ha^{-1}; some treatments received supplemental applications of N, and one treatment received only a cover crop of sericea lespedeza. Foliar P levels in these treatments started out at sufficient levels but dropped to levels at or near the 0.1 critical level after 6 years; a drop that was attributed to a "dilution effect" caused by the additional N fertilizer applications. Foliar P levels likely would have continued to drop and fallen below the critical level in the next few years. For minesoils, one, large, initial application of P may not be sufficient to support a forest stand through the first rotation. In addition, by addressing a N deficiency with fertilizer or a legume cover crop, P deficiencies in minesoils may be exacerbated.

The Effects of Organic Amendments on Tree and Ground Cover Growth in an Appalachian Minesoil

When this research project was initiated, the principal focus was on the soil-forming processes and the impact of organic amendments on those processes, all within the context of a forested ecosystem. The use of lysimeters provided strict control on the accumulation and cycling of organic matter and nutrients but also restricted the capacity of these systems to support unrestrained growth. The pine trees were planted so that soil building processes in the presence of trees could be studied. The integrity of the tree component, with respect to unrestrained growth, was only maintained for the first several years after which growth became restricted by the lysimeters. However, the basic soil-forming factors were less affected by these restrictions and continued to be influenced by tree presence and growth. The effect of organic amendments on tree seedling survival was also an initial part of this study. As a consequence, there were different numbers of trees growing in each tank, ranging from one to 10 trees per tank. The number of trees per tank also influenced how quickly the trees became pot-bound in the lysimeters. This difference in the number of trees per tank also confounded the ground cover data, preventing any comparisons from being made with normal field conditions.

In light of these experimental constraints, above-ground biomass data were presented to characterize the systems and to make comparisons among the three treatments. A review of the results from the first three years of the research reported by Schoenholtz (1990, 1992) and a review of pertinent literature is included to provide information on how this and similar systems perform under conditions that more closely match general field conditions (free of the constraints of the lysimeters and the different stand density and shading patterns caused by different numbers of trees).

The woodchip treatment had an average of 9.7 trees per tank in 1995, the control treatment had 7.3, and the topsoil treatment had 5.2 trees per tank. The rate of increase in average tree volume began to drop in the control and woodchip treatments after about the fifth year indicating that the trees in these tanks were becoming pot bound (Figure 2). Tree growth data was not intended to be used after the fifth year, so average tree volume data was presented with a dashed line and statistics were not performed on data past the fifth year. Average tree volume was significantly higher in the woodchip treatment than the control and topsoil treatments over the first 5 years of the experiment; volumes of the control and topsoil treatments were the same (Figure 2). In 1995, foliage samples collected for nutrient analysis were used to determine the average weight of 100 fascicles. The average weight of 100 fascicles for the woodchip treatment was 6.05 g and was not significantly different from that of the control treatment which was 6.74 g. The topsoil treatment had the highest average fascicle weight, 7.99 g (not significantly different from the control; significantly higher than the woodchip treatment). Foliage weight is indicative of tree vigor and productivity, and the foliage weight results show that trees in

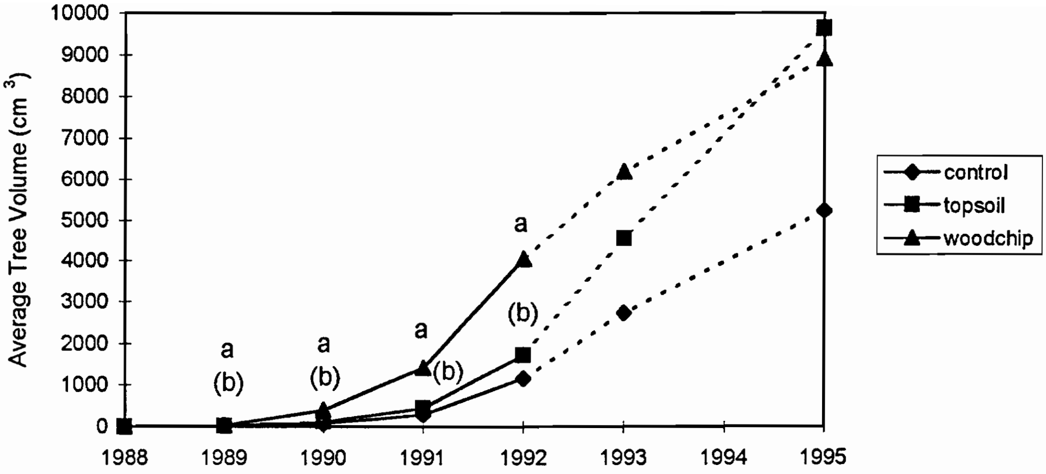

Figure 2. Effect of organic amendments on pitch *x* loblolly pine tree volume in an Appalachian minesoil. There were 7.3, 5.2, and 9.7 trees per tank for the control, topsoil, and woodchip treatments, respectively. For each date, different letters represent statistical differences at the α= 0.05 level. Statistical analysis was not performed on data after 1992.

the control and woodchip treatments were more negatively affected by restricted rooting volume compared to the trees in the topsoil treatment.

A comparison of tree heights with other research provides information on when tree growth became restricted by the lysimeter volume. Third year (1990), average tree heights were 58, 65, and 89 cm for the control, topsoil, and woodchip treatments, respectively. Moss et al. (1989) reported third year average pitch *x* loblolly pine tree heights of 52, 57, and 74 cm for a control, topsoil, and sawdust treatment placed on similar spoil material with unrestricted rooting volume in southwest Virginia. It appears that the trees in this experiment were growing freely up to at least the third year. Sixth year (1993), average tree heights were 191, 208, and 246 cm for the control, topsoil, and woodchip treatments, respectively. In Alabama, Bengston and Mays (1978) reported sixth-year loblolly pine heights for trees grown in minesoil with fertilizer and groundcover treatments that ranged from 520 to 610 cm. In this study, sixth-year average tree height was less than half of that reported by Bengston and Mays (1978) for trees growing unrestricted, providing an indication that tree growth in the lysimeters began to be negatively affected in the fourth and fifth growing seasons.

Average percent ground cover in the woodchip treatment was significantly lower than that of the control and topsoil treatments for the first three growing seasons due to the presence of phytotoxins in the fresh yellow-poplar woodchips (Schoenholtz 1992) (Figure 3). After five growing seasons, average percent ground cover was 68, 83, and 33 percent for the control, topsoil, and woodchip treatments, respectively (Figure 3). As with average tree volume, statistical analysis was performed on data up to and including 1992, which was the planned study period. The higher number of trees per tank in the woodchip and control treatments and the overall, rapid increase in tree volume, which occurred during the fourth and fifth growing seasons, caused increased shading of those tanks. The woodchip treatment had the highest number of trees per tank and the largest drop in percent ground cover from 1989 to 1992 (Figure 3). The topsoil treatment had the fewest trees per tank and smallest drop in percent ground cover; the control treatment was intermediate. While it is inevitable that under field conditions a stand of trees will reach crown closure and begin to shade out the ground cover, it is likely that the drop in ground cover in these treatments was premature. In a comparison of three ground cover treatments under loblolly pine cover, Bengston and Mays (1978) reported on the status of a fescue groundcover and a bermudagrass ground cover, both of which received 112 kg N ha^{-1} in the second growing season, and a sericea lespedeza ground cover with no subsequent fertilization. After six years, only scattered fescue plants and native grasses survived due to the shading of the pines, and the bermudagrass degenerated after the second fertilization leaving a fire hazard of accumulated mulch. The sericea lespedeza had 10 percent cover the first year, 70 percent cover after the second year and nearly complete cover and increasing density and vigor during the fourth, fifth, and sixth growing seasons (Bengston and Mays 1978). This demonstrates that not only was ground cover likely

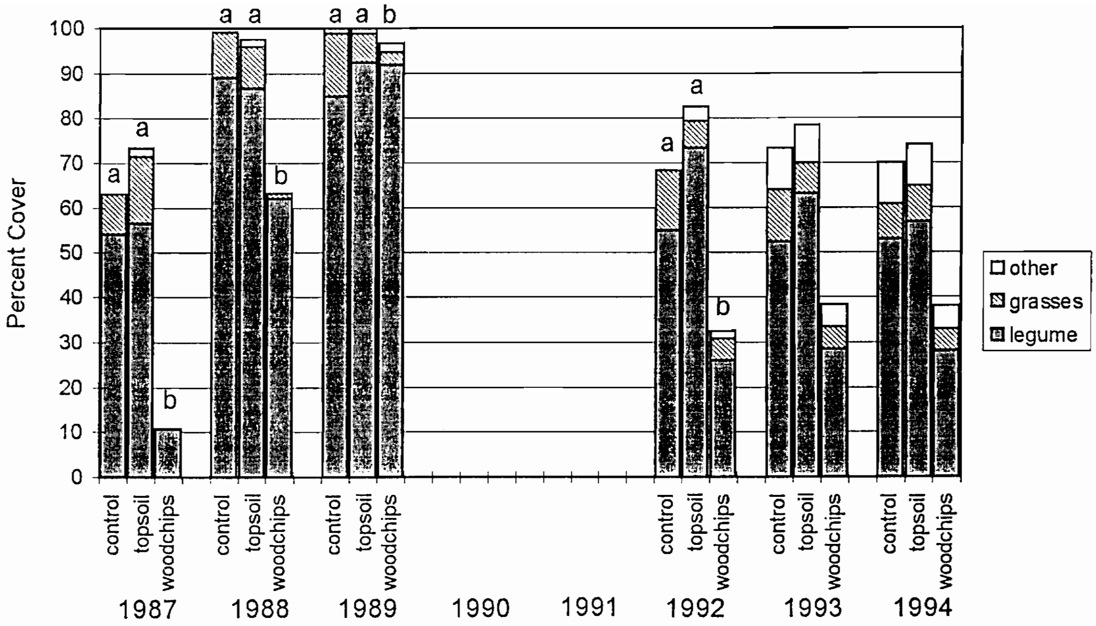

Figure 3. Effect of organic amendments on percent groundcover by life form in an Appalachian minesoil. For each date, different letters represent statistical differences at the α= 0.05 level. Statistical analysis was not performed on data after 1992.

being prematurely shaded out in this research, but that legumes may be able to persist under shaded conditions longer than grasses providing a N source at a time of increasing demand.

After 8 growing seasons, there were no statistical differences in the foliar concentrations of N, P, K, and Ca among the three treatments (Table 4). While specific nutrient critical levels have not been developed and tested for pitch *x* loblolly pine, studies have shown that nutrient levels between pitch *x* loblolly pine trees and loblolly pine trees were not significantly different (Johnson et al. 1991). Therefore, loblolly pine critical levels were used for comparison purposes. Despite the unnaturally high tree density in the lysimeters, the N concentrations in all three treatments were above the 1.1 percent N critical level (Allen 1987). The P and K concentrations in the three treatments were, however, below respective critical levels of 0.1 and 0.35 percent (Allen 1987). The P and K deficiencies in the three treatments, while probably a function of the pot-bound nature of the trees, are also probably indicative of naturally occurring deficiencies that warrant periodic monitoring under operational conditions.

Table 4. Effect of organic amendments on the foliar nutrient concentration of pitch *x* loblolly pine trees growing in an Appalachian minesoil.[1]

Treatment	N	P	K	Ca	Mg
			%		
			1988		
Control	1.36a[2]	0.13a	0.35b	0.26a	0.17a
Topsoil	1.43a	0.14a	0.38ab	0.25a	0.16a
Woodchips	1.52a	0.14a	0.41a	0.26a	0.16a
			1989		
Control	1.64a	0.16b	0.37b	0.31a	0.13a
Topsoil	1.72a	0.17a	0.38b	0.27a	0.11a
Woodchips	1.77a	0.16b	0.45a	0.26a	0.11a
			1995		
Control	1.40a	0.07a	0.22a	0.14a	0.10ab
Topsoil	1.46a	0.07a	0.22a	0.13a	0.09b
Woodchips	1.35a	0.07a	0.21a	0.15a	0.11a

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[1] Values are means of 6 replications.

[2] For each year, means within columns with different letters are significantly different at the 0.05 level.

The Effects of Organic Amendments on C and N Accumulation in an Appalachian Minesoil

The values for TOC and TKN that follow are net amounts that have accumulated since the start of the project. Minesoils in lysimeters under all three treatments had accumulated between 12 and 18 g TOC kg^{-1}, or 1.2 to 1.8 percent TOC, after eight years (Figure 4). TOC values in the eighth year were 12.7, 16.0, and 18.3 g TOC kg^{-1} for the control, topsoil, and woodchip treatments, respectively. The woodchip treatment had the highest TOC over 8 years, though not significantly different from the topsoil treatment in the eighth year. The control treatment TOC was not significantly different from the topsoil treatment except in the eighth year (Figure 4). Chichester and Hauser (1991) reported a TOC increase of 0.8 percent over six years in an unamended minesoil in Texas and a 0.6 percent increase on minesoils amended with topsoil. These TOC accumulation rates were about one-half those measured in this study largely due to differences in abiotic conditions.

In order to facilitate the comparison of these results with other research, the TOC concentrations were converted to OM percent using a conversion factor of 1.7 (Nelson and Sommers 1982). The OM concentrations were 2.2, 2.7, and 3.1 percent for the control, topsoil, and woodchip treatments, respectively. Daniels and Amos (1981), in a survey of the 135-ha Powell River Project site in southwest Virginia, reported the OM content (wet acid-dichromate digestion) of the A horizons of 5, 9, and 12-year-old spoils (n=15, 3, and 4, respectively). The average A horizon depths were 13.2, 11.3, and 27.0 cm, and the OM concentrations were 1.4, 3.5, and 2.3 percent,

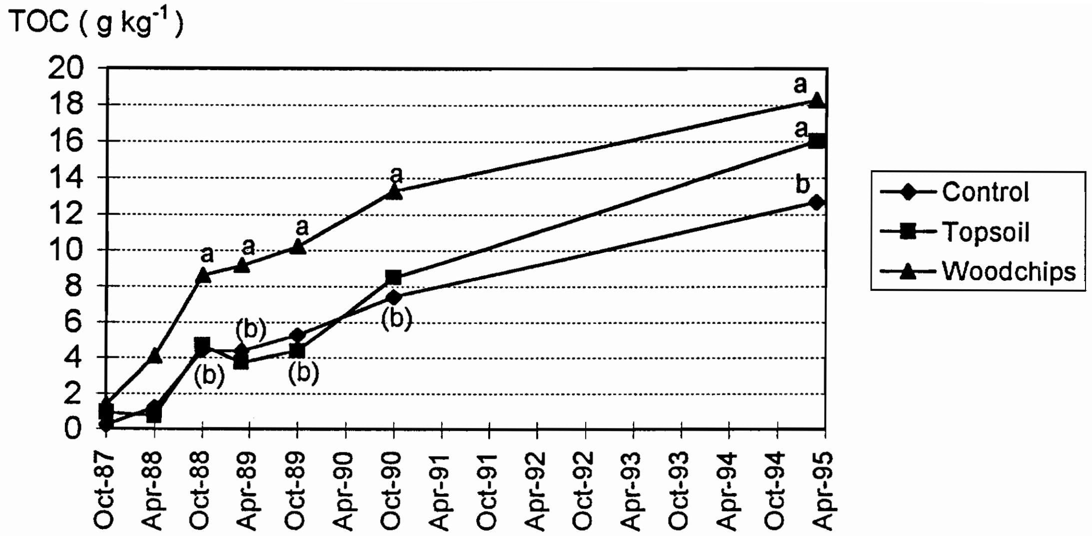

Figure 4. Effect of organic amendments on TOC accumulation in an Appalachian minesoil. For each date, different letters represent statistical differences at the α= 0.05 level.

respectively. The wet acid-dichromate digestion process can overestimate the OM content of minesoils due to the presence of coal fragments and reduced forms of Fe and Mn (Daniels and Amos 1982); with oxidation, this effect diminishes with time and may account for the decrease in OM concentration in the 12-year-old minesoils. Moss et al. (1989) reported third-year OM levels (wet acid-dichromate digestion) of 12, 9, and 45 g kg^{-1} for a control, topsoil, and sawdust treatment, respectively. These third-year levels are comparable to the eighth-year levels measured in this study due to positive error from the method used, and the sawdust treatment had over twice the OM applied as the woodchip treatment in this study. In a survey of 34 pre-SMCRA minesoils in southwest Virginia, Torbert et al. (1988) reported an average OM content (wet acid-dichromate digestion) of 17.2 g kg^{-1} and a standard deviation of 10.5.

The TOC accumulation rate constant (k) for the woodchip treatment (0.033 month^{-1}) was significantly higher than both the topsoil (0.008 month^{-1}) and control (0.013 month^{-1}) treatments which were not significantly different from each other. Some researchers have found that TOC accumulates faster on unamended minesoils than on amended minesoils (Chichester and Hauser 1991, Schafer et al. 1980). The TOC accumulation rate constant for the woodchip treatment may have been overestimated. Initially, much of the woodchip amendment would not have passed through a 2 mm sieve. As more of the woodchips decomposed, more could pass through the sieve for analysis. Therefore, decomposition of the woodchips was at least partly responsible for the higher rate of TOC accumulation over time.

TKN concentration was highest in the topsoil treatment over 8 years and was 1661 mg TKN kg^{-1} in the eighth year (Figure 5). The TKN values for the woodchip (1160 mg TKN kg^{-1}) and control

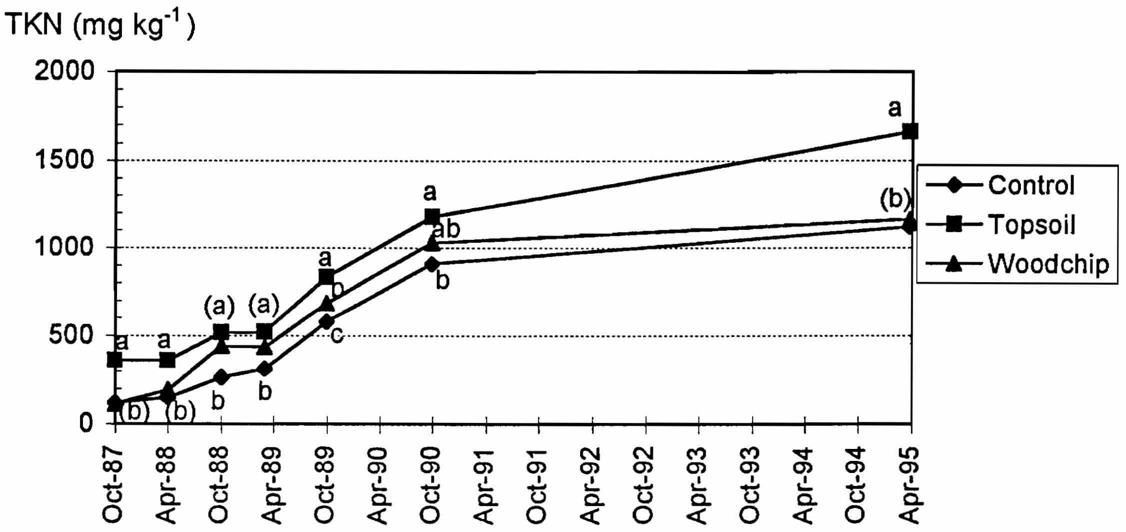

Figure 5. Effect of organic amendments on TKN accumulation in an Appalachian minesoil. For each date, different letters represent statistical differences at the $\alpha = 0.05$ level.

(1119 mg TKN kg^{-1}) treatments were not significantly different from each other after 8 years. Chichester and Hauser (1991) reported an increase from 500 to 1100 mg N kg^{-1} in an unamended minesoil, and an increase from 400 to 700 mg N kg^{-1} in three, topsoil-amended minesoils. Torbert et al. (1988) reported an average of 728 mg TKN kg^{-1} in the 0 to 10 cm layer of 34 minesoils with a standard deviation of 460. Moss et al. (1989) reported third-year TKN levels of 500, 330, and 1120 mg N kg^{-1} in a control, topsoil, and sawdust treatment, respectively. Third-year TKN values (1990) for this study were 908, 1175, and 1029 mg TKN kg^{-1} for the control, topsoil, and woodchip treatments, respectively (Figure 5). Inorganic N fertilizer was used to provide a N source in the study reported by Moss et al. (1989), while legumes were used in this study. The comparable levels of N in the sawdust treatment (Moss et al. 1989) and the woodchip treatment in this study were again due to an addition of over twice the amount of OM for the sawdust treatment.

The TKN accumulation rate constants were not significantly different among the three treatments (0.025, 0.026, and 0.037 month^{-1} for the control, topsoil, and woodchip treatments, respectively), but the rate of TKN accumulation in the woodchip and control treatment appears to have slowed by year 8 (Figure 5). This may be attributable to a difference in the number of trees per tank which, in turn, affected shading and ground cover. Therefore, the decrease in the rate of TKN accumulation that occurred after the third growing season in the woodchip and control treatments may be partly the result of tree-ground cover interactions.

The TOC and TKN concentrations were converted to a weight-per-unit-area basis using the fine-soil bulk density and the fine-earth fraction of the 0 to 10 cm layer. After 8 years, TOC in the control and woodchip treatments was not significantly different, and TKN in the control and topsoil treatments was not significantly different (Table 5). Accumulation rates for TOC were 1170, 1437, and 1408 kg TOC ha^{-1} yr^{-1} for the control, topsoil, and woodchip treatments, respectively. Roberts et al. (1988b) reported net increases of 700 kg TOC ha^{-1} yr^{-1} in an unamended control and 1500 kg TOC ha^{-1} yr^{-1} for both 22 and 56 Mg ha^{-1} sludge amended minesoils during the first three years. Using a 1.7 conversion factor to convert TOC (kg ha^{-1}) data to OM values, OM contents were roughly 15120, 18570, and 18190 kg OM ha^{-1} for the control, topsoil, and woodchip treatments, respectively. In Great Britain, Roberts et al. (1981) surveyed naturally revegetated china clay waste sites ranging from 16 to 116-years-old; 36 of 38 sites (ranging from 16- to 100-years old) had OM levels below 11000 kg OM ha^{-1}. This demonstrates the slow process of OM accumulation that can occur on minesoils allowed to naturally revegetated by invasion of native species.

Roberts et al. (1981) also surveyed N content in naturally revegetated china clay waste sites ranging from 16 to 116-years-old; the average N content was 923 kg ha^{-1} and N content was significantly correlated with waste age ($P<0.01$, $r^2=18$). Burger and Pritchett (1984) reported TKN contents of a mixed slash and longleaf pine (*Pinus palustris* Mill.) stand in Florida; values were 1280, 1020, and 770 kg N ha^{-1} for a control site, a burned and chopped site, and a bladed, disked, and bedded site, respectively. Wells and Jorgensen (1975) reported that a 16-year-old loblolly pine stand in North Carolina on undisturbed soils had 1753 kg N ha^{-1} in the mineral soil, 74 percent of the total N in this forest system. These 8-year-old minesoils have net accumulation amounts of N that are roughly half of the N found in a natural soil several thousands of years old due primarily to N-fixation by legumes.

Table 5. Effect of organic amendment on TOC and TKN (kg ha^{-1}) in an eight-year-old Appalachian minesoil.[1]

Treatment	Total Organic C	Total Kjeldahl N
	---------------- kg ha^{-1}	-------------
Control[2]	8893b[3]	784ab
Topsoil	10923a	1132a
Woodchips	10698ab	679b

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[1] Fine-soil bulk densities were 1.46, 1.42, and 1.33 for the control, topsoil, and woodchip treatments. Fine-earth fraction was 48, 48, and 44 percent for same.

[2] Values are means of 6 replications.

[3] For each date, means within columns with different letters are significantly different at the 0.05 level.

Net accumulation rates for TKN were 103, 149, and 89 kg TKN ha^{-1} yr^{-1} for the control, topsoil, and woodchip treatments, respectively. Roberts et al. (1988b) reported total N increases of from 21 to 150 kg N ha^{-1} yr^{-1} with the lowest accumulation rate in a sawdust-amended treatment. Dancer et al. (1977b) reported net annual N-fixation rates of 12 legumes species grown in mica and sand waste materials over two years; values for the top 11 species ranged from 281 to 108 kg N ha^{-1} yr^{-1} in the mica waste and from 151 to 32 kg N ha^{-1} yr^{-1} in the sand waste. Palaniappan et al. (1979) reported N accumulation rates of about 180 kg N ha^{-1} yr^{-1} on china clay wastes colonized by the tree lupine (*Lupinus arboreus*), and increases in total, inorganic, and mineralizable N were also associated with the presence of tree lupine. The accumulation rates of TKN in the minesoils of this study were comparable to the rates reported by the above research. As Bengtson and Mays (1978) reported, legumes can provide N in amounts similar to several applications of inorganic N fertilizer and can provide N in a form that is less transitory than fertilizer.

The above comparisons show that minesoils reclaimed with legumes can accumulate N at high rates. One further comparison demonstrates the productivity differences, with respect to N accumulation, that exist between traditionally reclaimed minesoils and minesoils reclaimed following the recommendations being tested in this study. Li and Daniels (1994) conducted a survey of 1 to 30-year-old minesoils on the Powell River Project in southwest Virginia. These minesoils were traditionally reclaimed with intensive grading and surface smoothing, and ground cover was dominated by tall fescue and sericea lespedeza. Natural invasion of trees occurred only after about 20 years and species composition and growth was poor. The estimated rate of N accumulation for these minesoils was 26 kg N ha^{-1} yr^{-1}. These conditions contrasted with those of the minesoils in this study show that the productivity of trees planted into traditionally reclaimed areas will likely be unacceptably unproductive.

C Mineralization

Organic C quality is an important determinant of C and N cycling. A C source that is highly resistant to decomposition will provide very little available N due to low C mineralization rates (Berg and Staff 1981, Zak et al. 1993). Quality of organic matter can be evaluated by studying the activity of heterotrophic microbes that are responsible for decomposing and mineralizing organic matter, and microbial activity is partly reflected by the amount of CO_2 evolved from the system. During the first two years of the study, the woodchip treatment showed significantly higher in-situ CO_2 evolution than both the topsoil and control treatments (Table 6). However, by the seventh year, differences in CO_2 evolution rates were much smaller among the three treatments. Over 7 years, the control and topsoil treatments had probably accumulated more readily mineralizable forms of C causing an increase in CO_2 evolution rates. The CO_2 evolution rate in the woodchip treatment remained high throughout but essentially unchanged over the same time (Table 6). In-situ CO_2 data collected monthly for the first two years showed the expected seasonal fluctuations, with the topsoil and control treatments not significantly different from each other from August, 1987 to December, 1988 (Schoenholtz 1990). The woodchip treatment CO_2 evolution rate was significantly higher than both for most of this time, with roughly double the CO_2 evolution in the spring and summer months. It is likely that CO_2 evolution in the woodchip treatment was initially high due to the addition of a readily-mineralizable C source. As this supply decomposed, root respiration and microbial decomposition of C accumulated from litter and fine-root turnover sources began to

Table 6. Effect of organic amendment on in-situ CO_2 evolution in an Appalachian mine soil.

Treatment	Evolved CO_2
	— mg CO_2 m^{-2} $hour^{-1}$ —
October 1987	
Control[1]	108b[2]
Topsoil	125b
Woodchip	220a
October 1988	
Control	102b
Topsoil	110b
Woodchip	202a
October 1994	
Control	196b
Topsoil	211ab
Woodchip	221a

[1] Values are means of 6 replications.

[2] For each date, means within columns with different letters are significantly different at the 0.05 level.

compensate for the reduction in labile C from the woodchips, keeping the overall CO_2 evolution rates roughly the same over time. Ewel et al. (1986) reported in-situ CO_2 evolution rates from a 29-year-old slash pine (*Pinus elliottii*) stand in Florida; the yearly average value was 280 mg CO_2 m^{-2} hr^{-1} measured with soda-lime traps.

The CO_2 evolution rates from the three treatments in this study were nearly that of a rotation-aged stand in a warmer, wetter environment. Ewel et al. (1986) also determined that root respiration accounted for roughly 50 percent of total evolved CO_2 measured in the stand.

The C_o incubation experiment was initiated to allow the removal of variation associated with different environmental conditions and with root respiration. Soil cores were subjected to identical moisture, temperature, and nutrient conditions in order to maximize C mineralization. CO_2 evolution was monitored for 10 weeks, beginning one week after moisture replenishment (Table 7). The results from the laboratory incubation (C_o) experiment showed that the woodchip treatment had the highest C_o and the control had the lowest C_o; the same pattern in CO_2 evolution among the treatments was found with the in-situ experiment. However, overall variability, particularly in the woodchip treatment, prevented statistical differences from being found (Table 7). While not statistically different, the values for C_o and k were indicative of the fundamental changes to the minesoil system caused by the organic amendments. Not surprisingly, the woodchip treatment, with the highest TOC concentration, had the highest microbial activity as reflected by CO_2 evolution. But, the rate constant for CO_2 evolution (k) for the woodchip treatment (0.158 $week^{-1}$) was in between that of the control (0.167 $week^{-1}$) and topsoil (0.122 $week^{-1}$) treatments (Table 7). The control treatment had the lowest C_o but the highest k indicating the forms of C that had

Table 7. Effect of organic amendments on the C Mineralization Potential (C_o) and rate constant (k) of an Appalachian minesoil.

Treatment	C_o	S.D.	k	S.D.
	— mg C/100g. soil —		—— week $^{-1}$ ——	
Control[1]	77.90a[2]	18.08	0.167a	0.054
Topsoil	92.10a	15.40	0.122a	0.056
Woodchips	105.55a	42.03	0.158a	0.052

[1] Values are means of 6 replications.

[2] For each date, means within columns with different letters are significantly different at the 0.05 level.

accumulated in the control treatment were more easily mineralizable than the forms of C in the other two treatments. The topsoil treatment had the intermediate level of CO_2 activity in both experiments and the lowest value for k due to the more recalcitrant forms of humus-C likely found in a topsoil amendment (Table 7). Harris and Riha (1991) used this same process for estimating C_o and k on different types of forest floor litter from New York. Laboratory incubations of red pine (*Pinus resinosa* Ait.) litter sampled at intervals over 1 year and 7 months had an average k of 0.102 $week^{-1}$.

In order to better gauge the status of TOC accumulation and the relative quality of TOC in the treatments after 8 growing seasons, a ratio of C mineralization potential (C_o) to TOC was calculated. The C_o/TOC ratio was 0.061, 0.058, and 0.058 for the control, topsoil, and woodchip treatments, respectively. The nearly identical C_o/TOC ratios for the three treatments shows that after 8 growing seasons, the quality of the C was virtually the same, and that differences in CO_2 evolution and C_o are more a result of the relative amount of TOC than of the TOC quality.

Nitrogen Mineralization

N is the mineral nutrient that plants require in the largest amount and that is often the most limiting in young minesoils (Woodmansee et al. 1978). Adequate pools of N and functioning N cycles must be established if plant requirements for N are to be met (Bradshaw et al. 1982). The accumulation and mineralization of C in a minesoil are important factors in determining N mineralization, but may not be the only important determining factors. In a survey of 11 minesoils and two native soils, Stroo and Jencks (1982) found that microbial respiration was not significantly correlated with total N or mineralizable N. Harris and Riha (1991) reported that CO_2 evolution was not significantly correlated with net N mineralization for incubated litter from red pine and two other species sampled over the same time period. Reeder and Berg (1977) incubated samples of shale regolith, fresh spoil, a vegetated spoil, and a native, undisturbed soil from Colorado. All of the geologic materials had similar CO_2 evolution rates and amounts, yet the shale and fresh spoil mineralized negligible amounts of NO_3^--N and the vegetated spoil and native soil mineralized 49 and 75 mg NO_3^--N kg^{-1}, respectively during a 168-day incubation. Woods and Schuman (1986) reported that while microbial biomass was linearly related to soil organic C and N concentrations, respiration and N mineralization depended on other factors in addition to OM concentrations. An examination of the factors that influence N mineralization, as measured by the anaerobic, aerobic, and buried-bag procedures, follows.

All three of these methods provide information on a different aspect of N mineralization, yet taken together, they provide a clearer assessment of N cycling in these minesoils. The anaerobic N mineralization method was designed as an easy, repeatable, and precise method that provides a N availability index. This index must then be related to field conditions and response to N fertilization so that it can be used as a predictive tool (Keeney 1982). The aerobic N mineralization method was developed to estimate the total pool of mineralizable N (N_o) in a soil. Consistent conditions of temperature and moisture, used in a long-term incubation, provide a thorough analysis of N mineralization and allow for meaningful relative comparisons. The buried-bag procedure was designed to minimize the effects of sample pretreatment and laboratory conditions that make correlation of results necessary. Field incubated samples are subjected to environmental conditions that affect N mineralization, thus providing an estimate of N mineralization that can be directly related to actual N mineralization under natural conditions (Plymale et al. 1987).

The anaerobic N mineralization index (An-N) in 1995 was 51.3, 80.0, and 50.2 mg NH_4^+-N kg^{-1} for the control, topsoil, and woodchip treatments, respectively. An-N for the topsoil treatment was significantly higher than the control throughout the study period (Figure 6). The An-N for the woodchip treatment showed a decline after 1989 and was not significantly different than the control treatment after 8 years. Torbert et al. (1995) reported on the N status of a southwest Virginia minesoil planted with loblolly pine and interplanted with either black locust (*Robinia psuedoacacia*) or black alder (*Alnus glutinosa*). After nine years, An-N values were 60.5, 68.6, and 68.1 mg kg^{-1} for the control, black locust, and black alder treatments, respectively. Powers (1980) reported that An-N (14 day incubation at 30°C) was correlated with total N, and 50.6 mg kg^{-1} were mineralized from the 5 to 15 cm depth in a 6-year-old conifer plantation in northern California. Shumway and Atkinson (1978) found a significant response to N fertilization when An-N values were less than 46 mg kg^{-1} in Douglas fir (*Psuedotsuga menziesii* (Mirb.) Franco) stands in western Washington and Oregon.

The aerobic N mineralization potential (N_o) was 112, 157, and 118 mg N kg^{-1} for the control, topsoil, and woodchip treatments, respectively in 1994, 7 years after treatment (Figure 7). The 1994 samples for N_o determination were taken December 8, while N_o samples for all previous years were taken on October 1. N_o for the woodchip treatment was not significantly different than the topsoil treatment in the first and second years; but, as readily-mineralizable forms of TOC were decomposed, the N_o of the woodchip treatment dropped to the same level as the control by 1994,

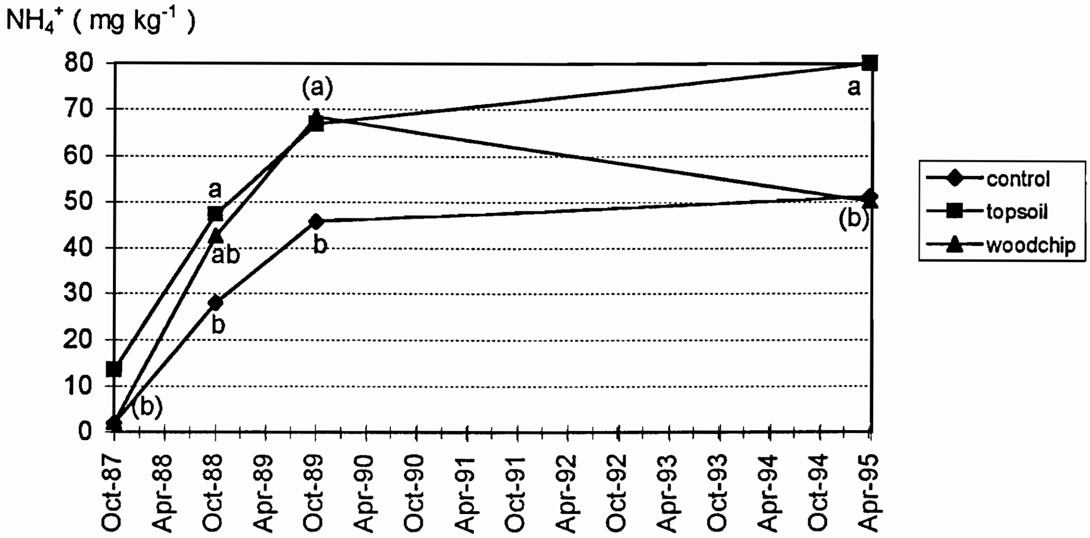

Figure 6. Effect of organic amendments on the Anaerobic N Mineralization index (An-N) of an Appalachian minesoil. A letter in parentheses applies to the two closest data points. For each date, different letters represent statistical differences at the α= 0.05 level.

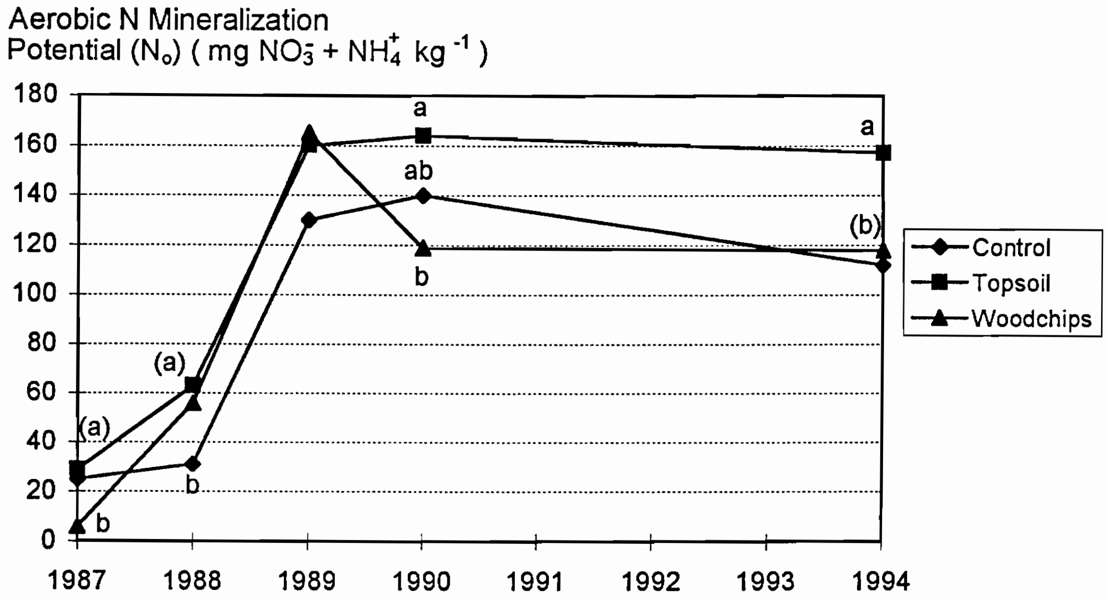

Figure 7. Effect of organic amendments on the Aerobic N Mineralization Potential (N_o) of an Appalachian minesoil. A letter in parentheses applies to the two closest data points. For each date, different letters represent statistical differences at the α= 0.05 level.

the seventh year (Figure 7). The N_o was not significantly different among the three treatments in 1989, the third year after treatment. The N_o for the topsoil treatment was significantly higher than the N_o for the control throughout the 7 year time period except for the third year. The decline of N_o in the woodchip and control treatments follows the decline in the rate of TKN accumulation in both treatments (Figure 7), and again may be linked to the drop in legume ground cover caused by the higher number of trees in the woodchip and control treatments. The An-N index and N_o data reflect the same relative relationship among the three treatments throughout the study period. The similarity between the results of these two methods supports the use of the An-N index method for relative estimates of N supply.

A ratio of N_o to TKN was determined for the study period; the 1995 ratio was calculated using the December 8, 1994 data for N_o and the April 1, 1995 data for TKN (Figure 8). The N_o/TKN ratio is a measure of the quality of the organic N found in the treatments. As with the C_o/TOC ratio, the N_o/TKN ratios were all roughly the same after 8 years (Figure 8). All three treatments showed an increase in the N_o/TKN ratio through 1989 (except for a drop in 1988 in the control treatment) then a decline over the next six years. The increase corresponded with the increase in ground cover percent and was probably caused by the input of legume fine roots and litter. Over time, this input declined while the input from the pine trees increased. Pine tree needles have a high lignin content and would decompose slowly and contribute little to the mineralizable N pool (Berg and Staaf 1981). Stanford and Smith (1972) reported a mean N_o/TKN ratio of 24 percent for nine Ultisols under various agricultural management practices. Burger and Pritchett (1984) reported N_o/TKN ratios of 4, 6, and 6 percent for a control, and two site-prepared, mixed-pine stands; however, the values for N_o were adjusted for temperature and moisture.

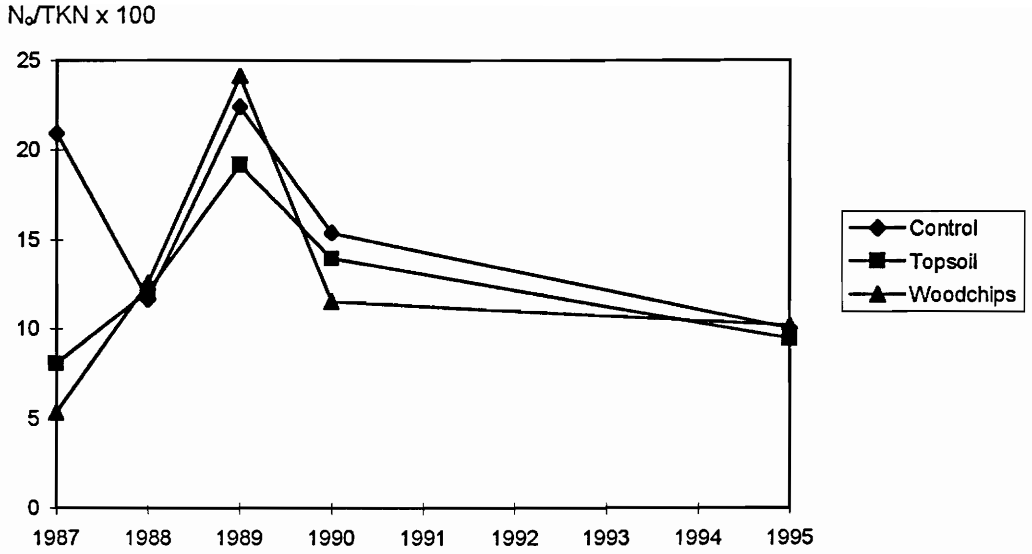

Figure 8. Effect of organic amendments on N_0 as a percent of TKN over 8 years in an Appalachian minesoil.

The laboratory methods used to determine N mineralization eliminated the effects of climate and site variables and so were useful for isolating the effects of OM quality and quantity. After 8 years, the effects of organic amendments on OM quality (as measured by the C_o/TOC and the N_o/TKN ratios) were unimportant. The statistically higher N mineralization in the topsoil treatment was likely due to the additional N in the added topsoil as the advantage was present from the outset. Plymale et al. (1987) measured N mineralization, using the buried-bag procedure, for a year in a mixed-oak and a mixed mesophytic stand in southern Ohio. In six of the seven incubation periods, initial ammonium pool size was the strongest correlate to N mineralization of measured chemical variables. While the woodchip treatment had the highest TOC concentration and the highest C mineralization values at year 8, the topsoil treatment had the highest measured N mineralization values.

Measurement of in-situ N mineralization using the buried-bag procedure incorporates all of the environmental and site variables that affect N mineralization in addition to the effects of OM quality and quantity. The buried-bag data were collected monthly for the first three years of the experiment (Schoenholtz 1990). These data showed that the lowest net N mineralization (or the highest net N immobilization) of the year occurred during August and September in each of the first three years. By the seventh year, all three treatments had net N mineralization during August and September (Figure 9). Net N mineralization in the control treatment was not significantly different from that of the woodchip treatment in August and was not significantly different from that of the topsoil treatment in September (Figure 9). Over seven years, the C/N ratio declined from about 50 in the control and woodchip treatments to about 23, and from about 39 to 19 in the topsoil treatment (Figure 9). The C/N ratios were above 30 for all three treatments during the first

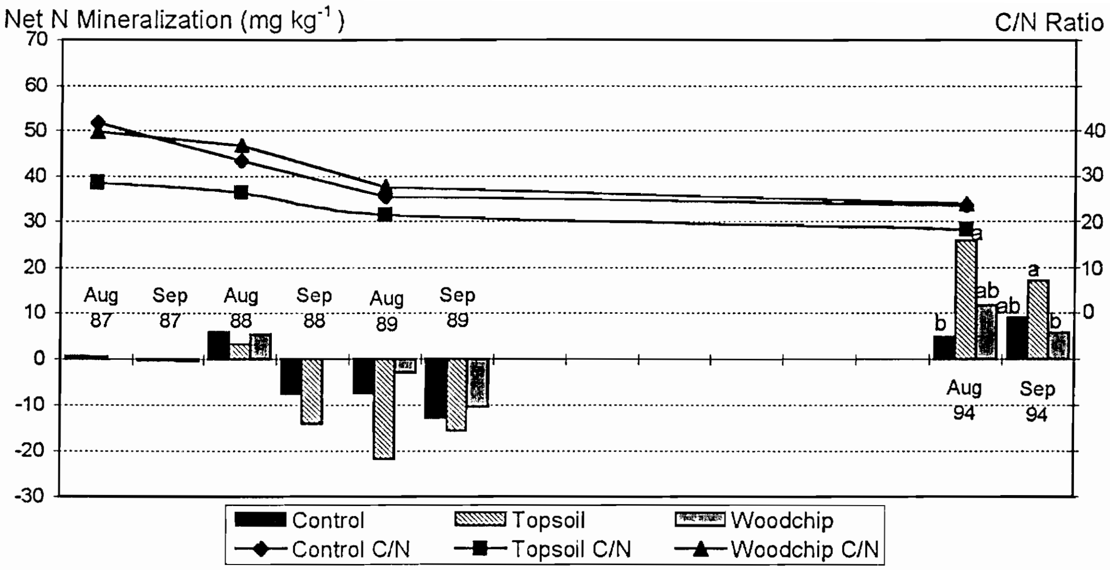

Figure 9. Effect of organic amendments on net N mineralization and C/N ratio in an Appalachian minesoil. Statistical means separation was not performed for mineralization data from the first three years or for the C/N ratio data. For each date, different letters represent statistical differences at the $\alpha = 0.05$ level.

three years when N immobilization was occurring. As C/N ratios dropped, net N mineralization began to take place. McClaugherty et al. (1985) reported that buried bags of forest litter accumulated N for the first two years until a critical C/N ratio, dependent on litter type, was reached.

If N limitation is one of the primary problems in minesoils, then research must determine the amount of N required to ensure short and long-term forest productivity and which treatments in this study met the requirements. A loblolly pine stand, at its most active growth stage, needs about 100 kg N ha^{-1} yr^{-1} (Wells and Jorgensen 1975). Internal recycling may account for 25 to 39 percent of that annual requirement (Wells and Jorgensen 1975, Switzer and Nelson 1972). Atmospheric deposition and leaching losses of N roughly equal each other (Bormann et al. 1977; Keeney 1980). The remainder of the annual requirement, roughly 60 to 75 kg N ha^{-1} yr^{-1}, must be mineralized from the forest floor and the mineral soil. The buried bag data provide a reasonable estimate of the ability of the mineral soil in these minesoils to meet the N demand unmet by internal recycling. However, the buried-bag data would not reflect the N mineralized and taken up directly from the forest floor.

The 1994 averages (for August and September) of 7, 22, and 9 mg N kg^{-1} $month^{-1}$ for the control, topsoil, and woodchip treatments, respectively (Figure 9) were converted to a yearly rate (see Table 2 for bulk densities and fine-earth fraction). Although no buried-bag data were taken for the other months of 1994, this yearly rate would likely represent a minimum ability to mineralize N, because August and September had the lowest N mineralization rates for the first three years of the study. After conversion to an areal basis, the in-situ N mineralization rates were 59, 180, and 63 kg N ha^{-1} yr^{-1} for the control, topsoil, and woodchip treatments, respectively. While the yearly rate for the topsoil treatment is roughly twice that of the other treatments, this is an indication that, at a minimum, all three treatments can meet the demand of 60 to 75 kg N ha^{-1} yr^{-1} from the soil system. The foliar N concentration data provide further evidence that the use of tree-compatible legumes has established sufficient N to support tree growth in all three treatments.

An attempt was made, in the topsoil and woodchip treatments, to create minesoils with similar total amounts of C and N but with different forms of each. Both treatments were very different from the control treatment with respect to size and quality of C and N pools. Yet, after 8 years, all three treatments have moved toward an equilibrium. Of the many factors that influence N mineralization, different sets of these factors combined to influence N cycling in each treatment. Nadelhoffer et al. (1983) reported buried-bag N mineralization data from 9 stands in Wisconsin. N mineralization rates in the 0 to 10 cm layer were roughly 100 kg N ha^{-1} yr^{-1} for three oak stands, 32.4 kg N ha^{-1} yr^{-1} in a red pine stand, and 80 kg N ha^{-1} yr^{-1} in a white pine stand. These data correspond well to the buried-bag data from this study. It was also reported that there was a trend that indicated that N mineralized more slowly from large SOM pools; this could be a contributing factor to the decline or lack of increase in N_o in all three treatments over the last 4 years. Plymale et al. (1987) reported that seasonal variation in N mineralization was more strongly dependent on moisture and temperature than on chemical variables. The woodchip amendment had a mulching effect that caused significantly higher moisture levels in the woodchip treatment compared to the control for at least the first three years of the study (Schoenholtz 1990). This higher moisture level contributed to the higher N_o values, compared to the control, during the first few years of the study. It was acknowledged that in comparisons between sites or soil types factors such as pH, P concentration, or C/N ratio may be just as important as moisture or temperature (Plymale et al. 1987). Nadelhoffer et al. (1983) reported that pH was significantly and negatively correlated with N mineralization. The topsoil amendment had an initial pH of 5.5, and the topsoil treatment had a significantly lower pH than the control and woodchip treatments through October 1989. The pH level in the topsoil treatment and the initially high N pool (lower C/N ratio) were probably the more important factors driving N mineralization. Pastor et al. (1984) reported N mineralization rates via the buried-bag method in 8 different forest stands in Wisconsin. N mineralization was significantly correlated with P concentration and negatively correlated with percent OM. The soil P and foliar P concentrations had dropped by the eighth year of the study in all three treatments, so P could have become limiting. Under field conditions, N deficiencies appearing as tree demand peaks could be reduced by addressing low levels of soil P.

CONCLUSIONS

Increased moisture and a slightly larger TKN concentration in the woodchip treatment (October 1988 to October 1989) were probably the dominant factors responsible for the significantly higher An-N and N_o compared to the control for the first two years. By 1995, TOC in the woodchip treatment on an areal basis was not significantly different from the control, so any mulching-effect advantage was likely minimized. In addition, TKN both on an areal basis and by concentration was not significantly different between the woodchip and control treatments after 8 years. As a result, N mineralization in the woodchip treatment was reduced. N mineralization in the topsoil treatment was probably driven by a lower initial C/N ratio, a lower pH level, and the larger pool of total N compared to the control. Though TKN on an areal basis in the topsoil treatment was not significantly different from the control after 8 years, the laboratory measurements of N mineralization remained significantly higher for 4 of the 5 measured years. N mineralization appears to have leveled off in the last few years in all three treatments, and the N_o/TKN ratio has also dropped. The decline in soil P concentrations in all three treatments cannot be ruled out as a contributing factor to the decline or lack of increase of N_o .

The constraints of the lysimeters used in this study prevent the direct correlation of minesoil productivity to tree productivity. The data show that differences in C and N accumulation and mineralization are becoming smaller and less important among the three treatments. Comparisons with other research have shown that all three treatments have the productive capacity, with respect to C and N, to support tree growth. These young minesoils may not have the buffering ability, with regard to total N supply, that would allow them to withstand large N removals that occur with some harvesting methods. However, the replacement of the N removed by sustainable harvesting methods, either through fertilization or reseeding with a tree-compatible, legume cover crop at the time of replanting, should return these minesoils to a productive level until they have accumulated enough N to buffer natural or managed disturbances.

The topsoil-amended minesoil accumulated and mineralized the most N, and maximum productivity would probably be realized under such conditions. However, productivity, as measured by tree growth, could not be determined due to experimental constraints. A comparison of the N accumulation rates from traditionally reclaimed minesoils and from the minesoils in this study showed a four-fold increase was achieved by following the principles established for reclamation forestry. This difference in N accumulation can be largely attributed to the replacement of tall fescue with legumes. The legumes used in the tree-compatible ground cover are less competitive for abiotic resources and provide additional organic N. In addition, minesoils with low compaction have been shown to accumulate more OM deeper and faster than compacted minesoils. For reclamation forestry to be successful, trees cannot simply be planted into areas reclaimed under the traditional agricultural model for forage crops. Tree planting must be part of a holistic approach to reclamation forestry as outlined here.

This research project showed that uncompacted, unamended topsoil substitutes of favorable material, planted with tree-compatible grasses and legumes, can provide the necessary conditions for trees and ground cover to survive and grow, and for C and N to accumulate and cycle. Topsoil substitutes so treated should be able to support and sustain forests for the long-term while minimizing the problem of N deficiency in minesoils. The creation of productive topsoil substitutes helps meet the reclamation requirements for bond release, and can save coal operators grading costs and costs associated with topsoil or organic matter amendments.

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Appendix A. Treatment combinations for each lysimeter.

Tank	N fertilizer	Organic amendment
1	Yes	Control
2	No	Wood Chips
3	Yes	Wood Chips
4	Yes	Control
5	No	Topsoil
6	No	Wood Chips
7	Yes	Topsoil
8	Yes	Topsoil
9	No	Topsoil
10	No	Control
11	No	Wood Chips
12	Yes	Control
13	Yes	Wood Chips
14	No	Topsoil
15	No	Control
16	No	Control
17	Yes	Wood Chips
18	Yes	Topsoil

Appendix B. Bulk Density, coarse fragment content, and particle size analysis on an Appalachian minesoil.

1989

Tank	Tot. Vol.	Tot. Wt.	Coarse Frag. Wt.	Whole Soil Bulk Density	Coarse Frag.	Coarse Frag. Vol.	Fine Earth Wt.	Fine Earth Vol.	Fine Earth Bulk Density	P.S.A.		
										S	Si	Cl
	cm^3	— g —		$g\ cm^{-3}$	%	cm^3	g	cm^3	$g\ cm^{-3}$	— % —		
1	1011	1760.4	1140.9	1.74	64.8	431	619.4	581	1.06	71	14	15
2	1282	1832.9	1344.3	1.43	73.3	507	488.6	775	0.62	71	14	15
3	1331	1738.8	1304.2	1.30	74.0	493	434.6	839	0.53	73	13	14
4	1488	2490.7	1655.0	1.66	66.1	625	835.7	864	0.96	67	15	18
5	1399	2033.1	1344.7	1.44	65.5	508	688.4	892	0.77	67	18	15
6	1737	2558.9	1994.5	1.45	76.8	753	564.4	985	0.58	69	14	17
7	1456	2547.8	1826.7	1.76	71.3	689	721.1	767	0.97	68	15	17
8	1212	2005.9	1439.3	1.65	71.7	543	566.6	669	0.83	66	15	18
9	1760	2657.5	1805.7	1.51	67.4	682	851.8	1079	0.79	70	15	15
10	1315	2509.6	1611.0	1.91	64.1	608	898.6	707	1.27	68	16	16
11	1620	2219.3	1573.7	1.37	70.9	594	645.6	1026	0.63	75	13	12
12	1385	2492.6	1587.0	1.80	63.3	599	905.5	787	1.16	66	17	17
13	1703	2289.4	1837.0	1.34	79.8	694	452.4	1009	0.44	75	12	13
14	1158	1908.2	1300.6	1.65	66.1	491	607.6	667	0.92	68	16	16
15	1425	2505.4	1656.5	1.79	65.1	625	848.9	800	1.12	72	13	15
16	1243	2054.4	1318.3	1.65	64.1	498	736.0	745	0.98	71	13	16
17	1595	2348.6	1771.2	1.50	75.4	669	577.4	927	0.66	73	13	14
18	1375	2015.6	1317.7	1.47	65.5	497	697.9	878	0.79	70	14	16

1995

1	5001.5	9501.8	5059.3	1.91	53.4	2075.9	4442.5	2925.7	1.52	62	23	14
2	5214.5	9314.2	5114.3	1.78	54.9	2161.7	4199.9	3052.8	1.37	63	23	14
3	5151.0	9379.6	5366.6	1.82	57.2	2476.3	4013.0	2674.7	1.50	64	23	14
4	4588.0	8700.3	4899.1	1.89	55.7	2008.1	3801.2	2579.9	1.47	62	24	14
5	5799.0	10108.3	5178.8	1.74	51.2	2128.6	4929.5	3670.4	1.34	60	23	17
6	5419.0	9297.1	5589.2	1.71	60.6	2434.3	3707.9	2984.7	1.23	66	21	13
7	5417.0	10025.5	5267.9	1.86	52.4	2287.2	4757.6	3129.8	1.52	62	26	12
8	5437.5	9674.9	5175.7	1.78	53.4	2071.9	4499.3	3365.6	1.34	61	26	12
9	5898.5	10344.5	5996.4	1.75	57.0	2488.8	4348.1	3409.7	1.28	60	28	12
10	4970.5	9354.9	5017.8	1.88	53.4	2075.3	4337.1	2895.2	1.50	63	24	13
11	5612.5	9074.1	4926.8	1.62	54.3	2100.5	4147.3	3512.0	1.18	65	23	12
12	5245.5	9412.4	4801.7	1.79	51.0	2014.8	4610.7	3230.7	1.43	64	23	13
13	4553.0	7705.7	3922.4	1.69	50.8	1927.0	3783.3	2626.0	1.44	65	22	12
14	5486.5	9421.7	4714.3	1.72	50.0	1968.3	4707.5	3518.2	1.34	61	27	12
15	5183.0	8385.3	4320.8	1.62	51.6	1824.1	4064.6	3359.0	1.22	62	25	13
16	3879.0	7105.2	3357.2	1.83	47.3	1514.5	3748.1	2364.6	1.60	63	23	14
17	4449.5	7506.6	4226.1	1.69	56.0	1866.0	3280.5	2583.5	1.27	71	17	12
18	4879.0	8809.1	4411.6	1.81	50.1	2125.7	4397.5	2753.3	1.65	64	24	12

Appendix C. pH in an Appalachian minesoil.

Tank	Jul-87	Oct-89	Mar-95
1	7.4	7.4	6.4
2	7.4	7.0	6.2
3	7.4	7.0	6.2
4	7.5	7.4	6.1
5	6.8	6.8	6.2
6	7.3	6.8	5.9
7	6.7	6.8	6.4
8	6.7	6.9	6.2
9	6.6	6.9	6.4
10	7.2	7.3	6.1
11	7.2	7.0	5.7
12	7.5	7.3	6.1
13	7.2	7.1	6.1
14	6.8	6.9	6.2
15	7.5	7.2	6.2
16	7.5	7.4	6.1
17	7.5	7.0	6.0
18	7.0	6.9	6.1

Appendix D. Electrical conductivity in an Appalachian minesoil.

Tank	Jul-87	Oct-89	Mar-95
		dS m^{-1}	
1	0.12	0.05	0.04
2	0.10	0.04	0.04
3	0.10	0.04	0.04
4	0.14	0.04	0.05
5	0.13	0.05	0.04
6	0.10	0.04	0.04
7	0.12	0.05	0.03
8	0.12	0.04	0.04
9	0.10	0.04	0.03
10	0.14	0.04	0.05
11	0.14	0.04	0.04
12	0.12	0.05	0.04
13	0.11	0.05	0.04
14	0.10	0.05	0.03
15	0.11	0.04	0.03
16	0.11	0.04	0.04
17	0.07	0.04	0.06
18	0.09	0.05	0.04

Appendix E. Extractable P in an Appalachian minesoil.

Tank	Jul-87	Oct-89	Mar-95
		mg P kg $^{-1}$	
1	7.03	4.92	4.13
2	0.68	7.41	5.28
3	1.73	5.96	6.40
4	1.92	6.78	5.27
5	4.02	7.65	4.52
6	2.50	7.96	6.21
7	2.92	6.10	6.40
8	2.99	6.23	4.92
9	4.41	5.11	6.30
10	1.36	5.30	5.39
11	1.95	4.11	8.61
12	1.82	5.01	4.73
13	2.20	6.84	6.65
14	3.60	7.14	5.33
15	2.23	5.96	1.71
16	1.82	6.93	6.23
17	2.34	9.12	4.82
18	3.87	8.12	6.00

Appendix F. Pitch *x* loblolly pine average volume in an Appalachian minesoil.

Tank	1991	1992	1993	1995
	----------------	cm^3	----------------	
1	248.1	983.8	2207.7	4262.9
2	1055.4	3077.3	5114.3	8306.7
3	1522.9	3884.7	6170.6	9102.5
4	224.3	1026.0	2712.0	5124.0
5	592.5	2329.8	7056.0	18764.5
6	1578.4	3950.6	5753.6	8270.4
7	300.1	1547.2	4497.0	8356.5
8	516.6	2033.9	4772.4	8378.8
9	197.8	852.9	3294.1	8817.3
10	315.8	1223.6	2951.9	5225.3
11	1584.2	5862.8	7958.6	10483.1
12	329.1	1271.5	2950.2	5343.8
13	1513.6	3949.5	6098.6	8629.8
14	333.5	1424.5	3787.7	7353.4
15	189.2	470.5	1572.9	4170.2
16	485.2	1919.6	4050.6	7267.7
17	1294.5	3604.0	6060.3	8609.3
18	770.7	2188.0	3998.7	6094.7

Appendix G. Average ground cover percent by life form in an Appalachian minesoil.

1987

Tank	legume	grasses	forbs	other	total
			%		
1	55	4	1	0	60
2	10	0	0	0	10
3	30	0	0	0	30
4	75	5	0	0	80
5	75	10	5	0	90
6	10	0	0	0	10
7	60	20	0	0	80
8	55	10	5	0	70
9	80	10	0	0	90
10	50	10	0	0	60
11	5	0	0	0	5
12	45	15	0	0	60
13	5	0	0	0	5
14	60	10	0	0	70
15	50	10	0	0	60
16	50	10	0	0	60
17	4	1	0	0	5
18	10	29	1	0	40

1988	legume	grasses	forbs	other	total
1	90	10	0	0	100
2	70	0	0	0	70
3	90	0	0	0	90
4	90	10	0	0	100
5	90	10	0	0	100
6	85	0	0	0	85
7	90	8	2	0	100
8	90	10	0	0	100
9	90	8	2	0	100
10	90	10	0	0	100
11	75	0	0	0	75
12	85	10	0	0	95
13	23	2	0	0	25
14	90	10	0	0	100
15	90	10	0	0	100
16	90	10	0	0	100
17	30	5	0	0	35
18	70	10	5	0	85

1989

Tank	legume	grasses	forbs	other	total
1	95	5	0	0	100
2	92	0	3	0	95
3	95	3	2	0	100
4	90	10	0	0	100
5	95	5	0	0	100
6	95	3	2	0	100
7	95	5	0	0	100
8	95	3	2	0	100
9	95	5	0	0	100
10	90	10	0	0	100
11	95	5	0	0	100
12	90	10	0	0	100
13	90	3	2	0	95
14	85	15	0	0	100
15	60	35	5	0	100
16	85	13	2	0	100
17	85	2	3	0	90
18	90	5	5	0	100

1992

Tank	legume	grasses	forbs	other	total
1	70	10	0	0	80
2	15	0	0	5	20
3	15	10	0	0	25
4	50	10	0	0	60
5	85	5	0	0	90
6	25	0	0	5	30
7	70	10	0	5	85
8	70	10	0	0	80
9	60	0	0	10	70
10	50	10	0	0	60
11	20	20	0	0	40
12	60	20	0	0	80
13	30	0	0	0	30
14	80	10	0	0	90
15	50	20	0	0	70
16	50	10	0	0	60
17	50	0	0	0	50
18	75	0	0	5	80

1993

Tank	legume	grasses	forbs	other	total
1	90	5	5	0	100
2	20	0	10	0	30
3	30	0	10	0	40
4	60	10	10	0	80
5	90	5	5	0	100
6	40	0	10	0	50
7	70	10	0	0	80
8	60	10	10	0	80
9	70	0	20	0	90
10	50	0	20	0	70
11	20	20	0	0	40
12	25	25	0	0	50
13	30	0	0	0	30
14	40	5	5	0	50
15	60	30	10	0	100
16	30	0	10	0	40
17	30	10	0	0	40
18	50	10	10	0	70

1994

Treatment	legume	grasses	forbs	other	total
control	53	8	9	0	70
topsoil	57	8	9	0	74
woodchip	28	5	5	0	38

Appendix H. Pitch *x* loblolly pine foliar nutrient concentrations in an Appalachian minesoil.

Tank	N	P	K	Ca	Mg
1988			%		
1	1.402	0.132	0.404	0.268	0.169
2	1.293	0.125	0.385	0.261	0.161
3	1.516	0.134	0.368	0.227	0.148
4	1.448	0.134	0.365	0.279	0.169
5	1.653	0.143	0.420	0.311	0.173
6	1.718	0.149	0.437	0.245	0.148
7	1.227	0.126	0.353	0.202	0.147
8	1.309	0.127	0.357	0.247	0.164
9	1.410	0.132	0.335	0.274	0.182
10	1.151	0.113	0.270	0.248	0.178
11	1.653	0.147	0.447	0.294	0.161
12	1.424	0.135	0.362	0.281	0.168
13	1.320	0.137	0.412	0.271	0.172
14	1.372	0.135	0.362	0.260	0.170
15	1.413	0.137	0.345	0.243	0.161
16	1.350	0.134	0.346	0.242	0.162
17	1.596	0.142	0.437	0.270	0.153
18	1.620	0.149	0.452	0.234	0.142

1988

Tank	N	P	K	Ca	Mg
1	1.771	0.162	0.371	0.312	0.130
2	1.839	0.169	0.468	0.234	0.107
3	1.847	0.169	0.460	0.263	0.101
4	1.503	0.146	0.344	0.325	0.120
5	1.672	0.148	0.389	0.209	0.085
6	1.896	0.173	0.472	0.231	0.111
7	1.730	0.159	0.376	0.268	0.108
8	1.790	0.159	0.384	0.297	0.114
9	1.683	0.144	0.381	0.306	0.109
10	1.659	0.156	0.365	0.374	0.160
11	1.547	0.164	0.430	0.303	0.130
12	1.634	0.153	0.393	0.241	0.098
13	1.781	0.163	0.430	0.291	0.113
14	1.762	0.165	0.346	0.319	0.132
15	1.645	0.160	0.361	0.317	0.130
16	1.651	0.160	0.376	0.299	0.130
17	1.719	0.162	0.412	0.268	0.124
18	1.664	0.158	0.407	0.243	0.105

1995

Tank	N	P	K	Ca	Mg
1	1.510	0.073	0.225	0.157	0.110
2	1.367	0.072	0.213	0.128	0.102
3	1.295	0.066	0.212	0.144	0.119
4	1.308	0.068	0.204	0.137	0.097
5	1.600	0.068	0.221	0.117	0.072
6	1.386	0.071	0.206	0.147	0.108
7	1.397	0.067	0.234	0.129	0.083
8	1.324	0.066	0.228	0.135	0.096
9	1.582	0.065	0.206	0.132	0.084
10	1.272	0.066	0.202	0.141	0.104
11	1.347	0.067	0.218	0.181	0.101
12	1.309	0.065	0.210	0.132	0.094
13	1.292	0.068	0.205	0.138	0.105
14	1.651	0.066	0.210	0.128	0.090
15	1.662	0.071	0.235	0.144	0.072
16	1.357	0.066	0.220	0.135	0.107
17	1.429	0.066	0.227	0.139	0.102
18	1.226	0.065	0.232	0.145	0.108

Appendix I. Total Organic C in an Appalachian minesoil.

All data are corrected for the initial, TOC concentration in the control treatement (July, 1987: control TOC=22000 mg kg^{-1}).

Tank	Oct-87	Apr-88	Oct-88	Mar-89	Oct-89	Apr-95
	------------------------- mg C kg^{-1} - --------------------					
1	604	1613	7011	3278	5548	11616
2	-2373	3580	9029	14176	12679	16713
3	99	4085	10089	12410	12477	15628
4	351	1310	2823	5145	6691	11984
5	1685	1229	5480	4873	4147	18270
6	-2171	4741	11300	12460	10863	23038
7	-542	875	4114	3203	4890	16008
8	1027	1684	4417	5682	5328	16263
9	2342	774	1431	1482	2595	14372
10	1411	452	2773	5649	4606	13336
11	3883	4085	7566	5195	7499	15206
12	-2626	452	351	805	5313	11614
13	3883	4438	5195	5801	7499	18043
14	1077	-2364	8263	2191	5463	15206
15	-1869	3631	6911	5397	5783	14301
16	3631	-254	6658	5952	3765	13289
17	4943	3782	8475	5144	10492	21056
18	14	2393	4417	4923	4038	16031

Appendix J. Total Kjeldahl N in an Appalachian minesoil.

All data are corrected for the initial TKN concentration in the control treatment (July 1987: control TKN=512 mg kg^{-1}).

	Oct-87	Apr-88	Oct-88	Mar-89	Oct-89	Oct-90	Apr-95
Tank	------------	------------	------------	mg TKN kg^{-1}	------------	------------	------------
1	87	139	298	301	504	908	942
2	93	173	529	503	746	1029	916
3	122	218	540	583	759	1029	824
4	196	207	259	375	704	908	870
5	462	352	532	487	817	1175	2031
6	99	236	471	474	768	1029	1351
7	383	427	697	573	798	1175	1705
8	334	369	541	591	820	1175	1564
9	325	323	513	446	842	1175	1617
10	148	121	253	260	597	908	901
11	76	173	397	365	507	1029	1070
12	93	139	273	317	539	908	1223
13	110	163	288	384	660	1029	1212
14	365	312	428	574	868	1175	1446
15	104	196	207	365	590	908	1458
16	88	111	299	262	541	908	1322
17	173	190	442	291	661	1029	1588
18	289	375	407	459	851	1175	1602

Appendix K. In-situ C mineralization in an Appalachian minesoil.

Tank	Oct-87	Oct-88	Oct-94
	--- mg CO_2 m^{-2} $hour^{-1}$ --		
1	73.1	116.1	205.2
2	186.0	317.6	207.0
3	247.4	150.4	224.3
4	91.0	69.0	192.2
5	130.7	107.3	241.5
6	287.1	143.6	234.9
7	122.6	122.9	203.0
8	148.2	109.9	220.5
9	120.2	144.8	188.1
10	104.7	86.9	202.2
11	189.5	222.8	239.2
12	108.7	153.6	178.4
13	194.4	139.3	221.1
14	113.3	88.8	199.2
15	157.4	98.4	172.6
16	111.8	86.0	224.7
17	214.0	236.5	202.0
18	113.3	84.7	225.1

Appendix L. C mineralization potentail (C_o) and k during laboratory incubation of an Appalachian minesoil.

Tank	C_o mg C 100 g^{-1} soil	k $week^{-1}$
1	63.27	0.221
2	73.42	0.220
3	103.95	0.107
4	81.79	0.120
5	102.26	0.079
6	80.68	0.195
7	105.19	0.113
8	107.21	0.064
9	76.20	0.197
10	69.28	0.207
11	181.42	0.086
12	76.74	0.188
13	71.68	0.163
14	71.43	0.185
15	111.81	0.083
16	64.49	0.182
17	122.13	0.178
18	90.32	0.093

Appendix M. N mineralization potential in an Appalachian minesoil.

1987

Treatment	N_o
	-- mg kg^{-1} --
Control	25.3
Topsoil	28.9
Woodchip	6.1

1988

Tank	
1	35.8
2	22.6
3	35.3
4	36.8
5	71.2
6	87.4
7	81.9
8	55.8
9	69.8
10	31.1
12	25.7
13	79.8
14	54.2
15	32.0
16	24.3
17	53.7
18	44.3

1989

Treatment	N_o
Control	129.7
Topsoil	159.9
Woodchip	164.7

	N_o
	-- mg kg^{-1} --
1990	
Tank	
1	117.5
2	129.0
3	151.3
4	191.7
5	135.2
6	112.4
7	188.1
8	186.7
9	167.0
10	103.1
11	90.9
12	172.9
13	101.4
14	124.6
15	162.5
16	92.1
17	126.9
18	184.1
1995	
Tank	
1	89.0
2	87.3
3	93.7
4	116.4
5	213.1
6	161.8
7	145.2
8	163.9
9	157.8
10	131.4
11	127.7
12	107.2
13	136.9
14	151.0
15	119.5
16	109.1
17	101.7
18	111.0

Appendix N. Anaerobic NH_4^+ mineralization in an Appalachian minesoil.

Tank	Oct-87	Oct-88	Oct-89	Apr-95
	------------------- mg NH_4^+ kg $^{-1}$ -------------------			
1	0.00	18.94	31.43	41.89
2	0.77	37.19	88.68	40.66
3	2.88	52.90	73.38	35.14
4	1.81	28.42	57.46	44.64
5	15.59	46.66	67.08	91.36
6	1.05	55.81	66.51	68.77
7	12.83	69.76	77.44	82.59
8	11.39	54.60	71.98	80.94
9	11.23	49.87	53.01	79.98
10	3.04	33.99	43.28	33.55
11	0.00	42.80	54.05	38.31
12	1.80	31.04	41.22	63.73
13	0.00	27.30	59.89	54.19
14	15.26	29.03	67.01	69.90
15	3.26	39.56	61.93	61.60
16	1.83	15.98	39.22	62.13
17	8.34	39.72	68.30	64.01
18	15.09	34.25	65.15	75.11

Appendix O. KCl extractable inorganic N from the buried-bag procedure in an Appalachian minesoil.

Date	Tank	Unincubated NO_3^-	Unincubated NH_4^+	Incubated NO_3^-	Incubated NH_4^+
		---------------- mg kg $^{-1}$			----------------
Aug-87	1	0.370	1.124	3.698	1.633
	2	0.181	1.509	0.095	0.890
	3	0.141	2.034	0.163	1.498
	4	3.213	1.506	1.080	1.875
	5	1.453	0.880	0.487	0.821
	6	0.143	1.445	0.227	0.741
	7	5.503	1.412	10.316	1.442
	8	3.026	1.398	4.557	1.256
	9	0.404	1.257	0.357	1.853
	10	0.128	1.496	0.135	1.449
	11	0.110	0.773	0.149	0.740
	12	0.310	0.791	0.232	1.614
	13	0.136	0.971	0.200	2.272
	14	0.519	1.116	0.295	1.589
	15	0.218	0.953	0.152	1.456
	16	0.194	0.847	0.111	1.198
	17	0.220	0.848	0.120	1.134
	18	2.587	1.680	0.279	0.626
Sep-87	1	0.361	1.234	0.142	1.087
	2	0.180	1.225	0.086	0.452
	3	0.237	1.546	0.090	0.782
	4	0.300	1.253	0.172	0.732
	5	0.414	1.282	1.101	1.143
	6	0.138	0.962	0.100	0.905
	7	1.894	2.528	0.638	1.755
	8	0.535	1.314	0.140	1.134
	9	0.238	0.735	0.083	0.996
	10	0.175	0.928	0.062	1.149
	11	0.187	0.622	0.095	0.782
	12	0.233	1.093	0.164	0.961
	13	0.187	1.344	0.056	0.828
	14	0.341	1.048	0.153	1.391
	15	0.159	0.990	0.107	1.081
	16	0.078	0.772	0.006	0.396
	17	0.203	1.030	0.050	0.480
	18	0.492	1.093	0.517	0.723

		Unincubated		Incubated	
Date	Tank	NO_3^-	NH_4^+	NO_3^-	NH_4^+
		--------------- mg kg $^{-1}$ ---------------			
Aug-88	1	0.052	1.607	4.648	15.858
	2	-0.089	1.103	1.685	8.440
	3	-0.130	1.072	1.120	11.120
	4	0.012	0.972	1.150	6.112
	5	0.264	3.522	3.914	10.043
	6	-0.140	1.193	1.080	6.132
	7	0.487	2.926	3.570	8.041
	8	0.103	5.584	1.943	5.807
	9	0.012	15.299	2.539	8.334
	10	0.002	2.756	1.191	5.023
	11	-0.130	2.866	1.070	5.487
	12	0.233	1.969	0.989	4.287
	13	0.163	2.171	0.536	2.977
	14	0.365	5.928	2.226	4.230
	15	0.193	4.519	1.695	4.650
	16	0.173	2.796	1.060	4.499
	17	0.092	3.350	0.707	2.796
	18	0.669	3.987	1.902	6.080
Sep-88	1	5.676	3.966	3.071	0.720
	2	0.189	2.884	0.222	0.830
	3	0.134	2.498	0.211	0.797
	4	19.478	3.513	5.257	0.963
	5	37.146	3.624	7.587	1.099
	6	0.266	2.034	0.244	2.133
	7	32.716	1.586	9.514	1.652
	8	20.202	1.099	6.159	1.220
	9	27.622	1.187	11.674	2.815
	10	13.295	5.501	6.825	0.930
	11	0.167	0.554	0.332	1.283
	12	10.314	0.378	8.061	1.095
	13	0.156	1.151	0.476	2.045
	14	17.212	0.478	13.668	0.944
	15	14.509	0.400	8.205	1.162
	16	9.121	0.289	3.501	1.261
	17	0.200	0.775	0.365	1.504
	18	19.980	0.755	20.534	2.394

		Unincubated		Incubated	
Date	Tank	NO_3^-	NH_4^+	NO_3^-	NH_4^+
		--------------- mg kg $^{-1}$ ---------------			
Aug-89	1	21.688	0.806	14.129	6.571
	2	0.422	0.988	4.262	6.128
	3	3.939	1.935	6.096	3.457
	4	27.332	1.431	2.085	2.308
	5	55.114	1.243	28.931	2.942
	6	26.425	1.613	11.004	4.596
	7	53.497	1.587	46.420	4.731
	8	66.942	2.133	41.265	5.115
	9	49.049	1.719	12.352	3.215
	10	14.129	1.794	10.803	2.852
	11	7.245	2.691	5.915	3.437
	12	22.091	1.673	21.990	2.449
	13	23.804	1.996	7.215	2.651
	14	68.358	2.780	47.836	3.821
	15	18.664	3.084	14.734	2.076
	16	11.912	3.477	2.387	1.663
	17	22.696	1.482	19.773	2.923
	18	34.188	2.810	6.954	4.691
Sep-89	1	25.339	0.000	11.531	0.837
	2	20.400	0.000	1.100	5.120
	3	16.470	0.000	13.043	1.996
	4	17.175	0.000	3.418	0.000
	5	23.899	0.000	1.760	0.000
	6	22.214	0.000	3.518	0.000
	7	29.763	0.000	6.026	0.000
	8	20.766	0.000	19.249	0.000
	9	31.077	0.000	4.965	0.000
	10	11.329	0.000	1.704	0.000
	11	12.841	0.000	9.263	0.000
	12	24.029	0.000	12.942	0.000
	13	17.780	0.000	1.866	0.595
	14	21.574	0.000	12.072	0.000
	15	28.766	0.000	11.632	0.000
	16	13.950	0.000	1.624	0.000
	17	12.539	0.000	2.188	0.988
	18	25.517	0.000	14.700	0.414

Date	Tank	Unincubated NO_3^-	Unincubated NH_4^+	Incubated NO_3^-	Incubated NH_4^+
		---------------- mg kg $^{-1}$			----------------
Aug-94	1	0.712	1.510	9.275	0.467
	2	0.050	2.625	5.072	3.085
	3	0.132	4.455	7.326	5.012
	4	0.107	3.172	3.325	2.998
	5	5.690	5.405	69.031	5.535
	6	0.095	4.529	19.839	5.859
	7	7.350	2.845	86.513	5.124
	8	2.710	3.000	20.584	1.912
	9	2.327	1.485	11.292	0.664
	10	0.008	2.795	1.932	7.897
	11	0.028	0.701	0.466	12.608
	12	0.142	1.573	4.254	3.183
	13	0.012	1.733	9.334	7.661
	14	1.642	3.385	22.564	3.832
	15	5.906	4.572	14.754	0.553
	16	0.331	2.138	1.549	1.525
	17	0.082	4.959	7.535	6.398
	18	0.371	1.697	2.449	7.699
Sep-94	1	0.383	6.253	11.758	0.981
	2	0.190	7.274	1.864	4.644
	3	0.235	2.970	4.172	0.899
	4	0.134	5.757	3.232	1.654
	5	6.692	11.526	42.982	2.560
	6	0.236	12.036	7.725	11.969
	7	4.920	7.867	34.174	1.814
	8	2.746	4.340	26.274	1.681
	9	5.474	4.739	16.410	0.000
	10	0.093	2.730	4.428	2.633
	11	0.123	4.917	1.538	10.331
	12	0.974	8.364	17.414	1.868
	13	0.075	3.602	9.159	3.383
	14	3.203	6.704	23.578	2.179
	15	3.125	5.422	31.817	0.339
	16	0.316	9.165	18.104	2.302
	17	0.215	7.547	10.698	7.206
	18	0.693	4.363	11.281	3.040

VITA

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