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Soil factors affecting reclamation of abandoned coal mine land and methods of soil preparation

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Introduction

In 1977 the United States federal government passed the Surface Mining Reclamation Act which established strict standards for coal mining operations to protect public safety and the environment. The law now requires coal mine operators to reclaim the land upon completion of mining activities and provides states with funding to reclaim mine land abandoned prior to 1977. Until this law was passed, coal mine operators were under no obligation to eliminate safety hazards such as vertical mineshafts and sheer highwalls or to restore the land to its predisturbance state. Consequently, many mining sites were abandoned once the coal was removed, leaving almost 70,800 hectares (200,000 acres) of land unable to support healthy native plant communities.

Coal mining not only visibly disrupts the aesthetics of the landscape, it disrupts soil components such as soil horizons and structure, soil microbe populations, and nutrient cycles that are crucial to sustaining a healthy ecosystem. Ecosystems function optimally as a process of recycling nutrients--a balance of growth rates and decomposition rates of plant and animal matter. Soil provides the foundation for this process, so its composition and density directly affect the future stability of the restored plant community.

Recontouring the land once mining is complete returns the landscape to a natural looking form, but the replaced soils do not resemble a pattern akin to normal evolutionary development. Soil components may be negatively affected by one or more events associated with coal mining: initial removal of soil from the site as mining activities begin, storing or stockpiling soil, respreading soil upon completion of mining activities, and post-spreading conditions. Reclamation strategies must address soil structure, microbe populations and nutrient cycling in order to return the land as closely as possible to its predisturbance condition and continue as a self-sustaining ecosystem.

Rebuilding Soil Structure

The first soil component addressed during reclamation is the structure of the soil itself as it is replaced onto the reclamation site. Soil structure includes soil aggregation, or the way in which soil particles are held together, and the size of the particles comprising the layers at different depths. In the case of coal mine land, it is also important to consider soil pH because acidic soils are a common by-product of mining.

Soil aggregation

Soil aggregation affects the degree to which oxygen, water and nutrients flow through the soil (Tomlinson, 1980; and Lindemann et al. 1984) and may reduce erosion potential (Elkins et al. 1984). Aggregate structure breaks down as successive layers of soil are removed and stockpiled

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elsewhere on the site when mining begins. The resulting compaction reduces water holding capacity and aeration.

The degree to which soil is loosely constructed versus compacted can be altered during reclamation by the method of replacement used (McSweeney and Jansen, 1984; Visser et al. 1984). Compaction can be minimized by using a mining wheel rather than scrapers to dig stored soil. Transporting soil from the stockpile to the reclamation site on a conveyor belt with trundling action improves soil structure by breaking up massive aggregates. As smaller aggregates continue to tumble, they tend to acquire an agglomerative skin of fine particles which promotes loose soil structure. Minimal use of bulldozers to level soil at the reclamation site further reduces compaction.

Loosely constructed, or "fritted", subsoil is very important to plant root systems. The extent of the root system determines a plant's ability to maximize its surface area and access a greater volume of water and soil nutrients. Plants grown in fritted subsoil have root patterns with extensive vertical and lateral penetration (McSweeney and Jansen, 1984). Root patterns in compacted soils are limited to cracks occurring in the substrate and achieve little additional soil penetration.

Soil pH

Most plants achieve optimal growth in soil at neutral pH. Many metabolic processes are impeded or inhibited altogether in acidic environments. Mining typically exposes sulfur-containing pyrites that oxidize to sulfuric acid when exposed to oxygen, water, and certain aerobic bacteria, leaving soil pH at 2.2 - 3.5 (Gitt and Dollhopf, 1991; and Gould, et al. 1996). High soil acidity inhibits plant root growth by limiting the amount of nutrients available for uptake (Lawrey, 1977; and Gitt and Dollhopf, 1991).

Acidic minesoils can be effectively neutralized after they have been respread at the reclamation site by applying either cement kiln dust (CaO) or limestone ($CaCO_3$) (Gitt and Dollhopf, 1991). Lime application rates must account for both past and future pyrite oxidation in order to maintain neutral soil pH levels over time. Gitt and Dollhopf used a computerized automatic rapid weathering apparatus (CARWA) in a laboratory setting to estimate lime requirements. Application amounts were based on acid production in pyritic soils exposed to simulated weathering conditions.

The techniques for incorporating lime into soil need improvement. Available technology failed to incorporate lime applications consistently to the depths attempted by researchers, 35 cm with a chisel plow and 100 cm with a trench-excavating machine (Gitt and Dollhopf, 1991). Actual depth of incorporation, measured by acid neutralization, was achieved to a depth of 10-30 cm, approximately one third of that desired. Root penetration typically extended only to the depth of lime incorporation which, at most, was 100 cm. The achieved depths may not be sufficient for plants such as grasses with root systems extending 2-3 m below the surface. Developing techniques that mix lime into the soil during rather than after respreading may improve the thoroughness and depth of lime incorporation.

Recharging Soil Microbe Activity

Soil microbe populations must be addressed deliberately as another soil component. Their activity declines when soil layers are disrupted and is slow to resume independently. Soil microbes include several bacterial species active in the decomposition of plant material as well as fungal species whose symbiotic relationship with many plants facilitates the uptake of nitrogen and phosphorus in exchange for carbon. They produce polysaccharides that improve soil aggregation and positively affect plant growth (Visser et al. 1984; Malope et al. 1987; and Williamson and Johnson, 1991). Sites with an active soil microbe community exhibit stable soil aggregation, whereas sites with decreased microbial activity have compacted soil and poor aggregation (Edgerton et al. 1995).

Bacteria

When soil layers are removed and stockpiled, the bacteria inhabiting the original upper layers end up on the bottom of the pile under compacted soil. A flush of activity occurs in the new upper layer during the first year as bacteria are exposed to atmospheric oxygen (Williamson and Johnson, 1991).

Microbial activity decreases with depth and time as topsoil continues to be stored during mining operations (Harris et al. 1989). After two years of storage there is little change in bacterial numbers at the surface, but less than one half the initial populations persist at depths below 50 cm. Microbial activity, measured in ATP concentrations, plummets to very low levels within a few months. Microbial respiration and microbial biomass carbon at deeper levels of a stockpile may not be significantly reduced. Response to glucose is slower by microbes at all depths, suggesting that metabolic rates decrease with time (Visser et al. 1984).

In one study, amending replaced topsoil with hay and processed sewage sludge was more effective than topsoil inoculation in stimulating bacterial growth and activity, particularly for bacteria that oxidize ammonia (Lindemann et al. 1984). Bacteria present in the soil require a source of readily oxidizable carbon provided by the hay and sludge to fuel metabolic activity and stimulate nitrogen cycling. Topsoil contains carbon, but it is often in the form of coal or other humic material mixed in during soil replacement and is not readily usable.

Mycorrhizal fungi

The hyphal network established by mycorrhizal fungi breaks when soils are initially moved and stockpiled (Gould et al. 1995). It is well documented that mycorrhizal associations stimulate plant growth (Clark, 1969; Mosse, 1973; Furlan and Fortin, 1973; Crush, 1973b; Daft and Hacskaylo, 1974) and plant uptake of phosphorus and nitrogen (Daft and Hacskaylo, 1976). There is little decrease in viable mycorrhizal inoculum potential during the first two years of storage (Miller et al. 1985). Viability of mycorrhizas in stored soils decreases considerably after that, possibly to levels only 1/10 those of undisturbed soil (Rives et al. 1980).

Miller et al. (1985) indicate that soil water potential is a significant factor affecting mycorrhizal viability. When soil water potential is less than -2 MPa (drier soil), mycorrhizal propagules can survive for greater lengths of storage time; when soil water potential is greater than -2 MPa, length of storage time becomes more important. In drier climates, deep stockpiles may not threaten mycorrhizal propagule survival. In wetter climates, shallow stockpiles are more important to maximize surface-to-volume ratios with regard to moisture evaporation.

Mycorrhizal propagule densities remain low immediately after reclamation on uninoculated sites, but re-establish themselves after a period of two years (Williamson and Johnson, 1991; and Gould et al., 1995). This coincides with the appearance of host plants, such as tall fescue, that are more conducive to mycorrhizal colonization than those first appearing on the site (winter wheat) (Gould et al. 1995). Mycorrhizal propagules existing in the topsoil may be stimulated by the presence of suitable host plants, though Gould et al. encourage further research. Lindemann et al. (1985) found that covering respread soils with 30 cm of topsoil (without mycorrhizal inoculum) also stimulated host colonization by mycorrhizal fungi whereas using hay, topsoil with inoculum, or sewage sludge had no effect. Sewage sludge may suppress mycorrhizal development by increasing the phosphorus available to host plants (Daft and Hacskaylo, 1976).

It is especially interesting to note that soil microbe populations persist in stored soil and can be stimulated during reclamation by charging the system with a source of organic carbon or by adding suitable host plants. Inocula cultured from indigenous microbes that are costly and in limited supply may not be necessary.

Re-establishing Nutrient Cycles

Nutrient cycling is very closely linked to soil microbe activity. It is the process by which carbon, nitrogen, and phosphorus are reused within an ecosystem due to the metabolic activity of plants and soil microbes. Carbon and nitrogen cycles in particular are disrupted as soil microbe populations decline and must be re-established during reclamation.

Carbon cycle

Organic carbon fuels the metabolic activity of many soil microbes. Microbes obtain carbon through their symbiotic relationships with suitable host plants or from organic carbon available in the soil resulting from decomposition of plant and animal matter. As topsoil is removed from a mining site it is often mixed with underlying soil, considerably reducing the relative proportion of organic carbon (Visser et al. 1984). Little additional change in this proportion results from extended storage of soil.

Researchers frequently found the amount of organic carbon to be the limiting factor in stimulating microbial metabolic activity (Visser et al. 1984; Williamson and Johnson, 1991). Amending soil with bark (Elkins et al. 1984) or fertilizing and planting ryegrass (Williamson and Johnson, 1991) provides bacteria with enough organic carbon to stimulate metabolic activity, measured by increased microbial carbon.

Nitrogen Cycle

Nitrogen can be taken up by plants as ammonium or nitrate. Soil nitrogen is usually in the form of ammonia (NH_3) or ammonium (NH_4) and must be oxidized to nitrate (NO_3) by bacteria, a process referred to as nitrification.

Removal and storage of topsoil does not greatly affect nitrogen availability possibly because it is removed from the site prior to disturbing the pyritic soils below. Available nitrogen remains high throughout the first year of storage and may be even higher than in undisturbed soil (Visser et al. 1984). Some nitrogen continues to be available through nitrification activity after 2-3 years in storage (Sorensen and Fresquez, 1991).

Significant levels of NH_4 may accumulate in the deep anaerobic zones of stored soil that result in high nitrification potential when exposed to oxygen after respreading (Visser et al. 1984; and Williamson and Johnson, 1990). Plants grown in this soil show little detriment to growth during the first year after soils are respread, possibly due to increased NO_3 availability (Visser et al. 1984). Excessive concentrations of NH_4 and soils with high salinity are toxic to nitrifying bacteria which may limit NO_2 oxidation, causing toxic accumulations of the latter (Sorensen and Fresquez, 1991). In arid sites, nitrate may leach down to 25-30 cm--depths that are inaccessible to newly rooting plants. Amending these soils with 15 cm topsoil during respreading stimulates nitrification and reduces leaching. During the first two years after reclamation, nitrification rates in reclaimed sites were less than those in undisturbed sites but approached levels similar to undisturbed sites after two years.

Nutrient recycling and availability on reclaimed sites is reflected in part by the rate of decomposition of plant material. Litter decomposition in mined land versus unmined land is often retarded during the initial months after reclamation (Lawrey 1977). The presence of heavy metals which reduce soil pH and the lack of an existing litter layer create an unfavorable microclimate for soil microbes responsible for breaking down organic matter. Decomposition rates begin to equalize after six months suggesting increased microbial activity, but the initial dearth of recycled nutrients could impede establishment of new plants. Elkins et al. (1984) demonstrate that amending minespoils with bark rather than topsoil significantly increases soil microbe activity and consequently decomposition rates but result in less available NO_3 than in unamended spoil. Oxidation of soil nitrogen to NO_3 may be impeded by acidic soils (Kormondy, 1984) or by the length time required by certain bacteria to become established.

Determining Effectiveness of Soil Reclamation

Once the reclamation plan is complete and vegetation has established, some assessment should be made to determine how closely the reclaimed site functions as an ecosystem compared to similar undisturbed sites. Reclamation of abandoned coal mine land is a very complex process. Most researchers agree that reclamation success must be measured by more than the presence of vegetation on the site. Soil microbes influence plant succession by facilitating maturation of soil composition. Edgerton et al. (1995) found a positive linear correlation between soil aggregate stability and microbial biomass carbon suggesting that measuring the productivity of the microbial community leads to reasonable assumptions about the quality of soil structure. Two methods for evaluating soil microbe populations and their metabolic activity have been proposed to determine the stability of a restored ecosystem.

Insam and Domsch (1988) recommend using the ratio of microbial carbon to total organic carbon to evaluate the status of an ecosystem. As an ecosystem reaches steady state conditions, the rate of heterotrophic respiration balances the rate of primary production. Consequently, the ratio of microbial carbon to total soil carbon reaches equilibrium. On a chronosequence evaluation of reclaimed open-pit mine sites, they found that while total soil carbon increased, the proportion of microbial carbon quickly increased and then declined over time. After 50 years, the reclaimed sites had not yet reached equilibrium. Therefore, neither the measure of microbial biomass carbon nor total carbon alone represents the stability of the ecosystem.

Bentham et al. (1992) developed a three-dimensional system measuring ATP, dehydrogenase activity, and ergosterol to classify habitats based on microbiological and physico-chemical characteristics. While their entire dataset includes other factors such as soil moisture content, type of ecosystem, restored versus undisturbed site, they found that using the selected three-dimensional system allowed distinction of different habitats. The results can then be used in conjunction with reference databases of undisturbed sites to evaluate success of restoration.

Conclusion

Reclamation must go beyond planting a new landscape by considering the land as an integrated system that functions above and below the ground. Project plans must include strategies that rebuild soil structure, stimulate soil microbial populations and re-establish nutrient cycles if this system is to reassemble. Researchers have demonstrated techniques that appear successful over periods of several years and have indicated that there is much more to learn about their long-range effects. It is unclear how frequently or for what length of time follow-up is done on reclaimed sites to compare their function with undisturbed sites. Funding continues to be available to coal mine operators and states to reclaim land on active and abandoned coal mine sites. Expanding follow-up efforts, particularly on sites that were abandoned for many years, may reveal valuable information that will guide the success of future reclamation activities.

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