SOIL MICROBIAL ECOSYSTEMS: IMPORTANCE FOR THE EFFECTIVE RESTORATION OF MINED LANDS[1]

by

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Abstract In many cases where mined lands are to be returned to productive use, the basic unit of resource is the soil system. This resource has often been badly degraded or even lost completely as a result of the mineral extraction activities carried out on the lands that it covers. In any restoration programme where plant growth is to be the end-use, for agriculture or conservation, the development of a self-sustaining soil system is of primary importance. This not only requires establishment of adequate nutrient levels and their efficient cycling, but also the development of a stable and open soil structure. The soil microbial community is of fundamental importance in fulfilling this objective. Both free-living micro-organisms and those involved in symbiotic relationships, such as mycorrhiza, have been demonstrated to be adversely affected by mining activities. It is suggested that these changes offer several opportunities for the reclamation researcher and practitioner. The soils affected may be classified in terms of undisturbed and semi-natural systems by measuring the size, composition and activity of the soil microbial community. Further, the effects of management practices may be quickly identified due to the sensitivity of this community to change. A programme of research investigating the applicability of microbial community measures has been established for those lands affected by opencast mining in the UK, and is proving to be both sensitive and consistent in its ability to discriminate between different ecosystems. It is suggested that this could be extended to other ecosystems.

Additional key words: Opencast mine restoration, soil microbial community, ecosystem classification.

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Introduction

The role of micro-organisms in the development and maintenance of soils as functional units has been recognised for some time by microbiologists (Alexander 1977), but has had scant attention from other groups of researchers. Morevover, their role in lands disturbed by mineral extraction industries has only been investigated to any great extent in recent years. Many of these approaches have been piecemeal, with little attempt to produce a synthesis of the importance of micro-organisms in these disturbed systems, or treatments designed specifically to harness those characterisitics of the soil microbial community likely to bring benefit in terms of ecosystem development.

The aim of this paper is to bring together some of the research carried out in the area and to provide some direction for future research.

Effects of soil disturbance and storage

One common operation performed on opencast coal mine sites is the stripping and storage of topsoil. There have been few studies over the period of most intense opencast mining activity, but there has been an increase in investigations in recent years. Barkworth and Bateson (1964) suggested that bacteria die out slowly in stockpiled soils, but recent work suggests that the microbial biomass declines rapidly on stripping and storage. Ross and Cairns (1981) have shown reduced mineralisation and nitrifying potentials in stockpiles. Visser et al (1984) found less microbial carbon in stockpiled soils, with little apparent effect on respiratory output, with the exception that there was a slower response to additions of carbon in comparison to controls. There was also little effect on decomposition potential, using cellulose as a bait. Harris and co-workers (1989) demonstrated that there was a fall in microbial biomass to as little as 6% of the amounts found in undisturbed control areas, in certain buried parts of soil stores. This work was followed by an investigation into the effects on the microbial community of the store construction process during the early stages of storage (Harris and Birch 1990a). It was demonstrated that on the day of store construction, microbial biomass had fallen to a value 60% of that of the unworked area from which the soil had been taken. Further, after 8 months of storage the value in the deepest part of the soil store (180-210 cm from the surface of the store) had declined to 40% of the control value, whilst the biomass in the top 0-30 cm had increased to a value of 105% of the control.

There is also considerable evidence of the effects of storage on particular groups of organisms. Abdul-Kareem and McRae (1984) demonstrated a significant decline in the numbers of vesicular-arbuscular mycorrhizal (VAM) propagules in soils stockpiled on landfill sites, a finding confirmed by Harris et al (1987) on opencast coal mine sites. The fungi as a group have also been shown to be particularly sensitive to disturbance and storage. Harris and Birch (1990a) demonstrated a 40% drop in numbers as a result of soil moving operations, further compounded by the anaerobic conditions which then developed in store. This sensitivity is most probably due to their growth habit and oxygen requirements. They form fine mycelial threads that ramify through the soil binding particles together, rendering them particularly sensitive to shear forces generated by earthmoving operations. In some cases, the numbers of fungi found have been as low as 3 orders of magnitude less than comparable undisturbed soils (Harris et al 1989). This has consequences for the normal function of a soil ecosystem, as fungi are of primary importance in the early stages of organic matter decomposition, with their ability to ramify into such material and begin the process of biochemical breakdown.

Changes during restoration

There are reports on the state of the soil microbial community in areas restored after opencast mining, but few systematic investigations to determine the causes or consequences of any changes with time or substrate condition.

Early work by Wilson & Stewart (1955 & 1956) indicated that strip-mine spoils possessed a microbial population capable of organic matter decomposition, even if the spoil was lacking a vegetative cover. They also noted low levels of nitrogen. To assess the effect of adding nutrients to spoil on decomposition a series of laboratory experiments were carried out (Hedrick & Wilson 1956). They reported the greatest increase in carbon dioxide evolution when nitrogen was added, whether alone or in combination with phosphorous, potassium, straw, or calcium hydroxide. Calcium hydroxide addition, to achieve a more favourable pH, was secondary in importance to N additions, whilst phosphorous and potassium additions had little effect.

In a study of the microbiology of an Appalachian strip-mine spoil, Wilson (1965) found markedly greater numbers of fungi, bacteria, and actinomycetes in 2 sites, 1 revegetated and one undisturbed land, when compared to unvegetated spoil. Wilson concluded that vegetation exerted a greater influence on the soil microflora than the low pH caused by sulphur oxidizing bacteria. The diversity of physiological groups was also greater in this revegetated spoil (i.e., ammonifyers, nitrifyers, nitrate reducers, cellulose degraders and polysaccharide producers).

Schramm (1966) demonstrated a relationship between the colonizing success of plant species in Pennsylvanian coal spoils and the presence of certain ectomycorrhizal fungi and nitrogen-fixing bacteria, work later mirrored by that of Daft and Nicolson (1974) in Scottish coal spoils. Schramm (1966) also noted generally low bacterial biomass in coal mine spoils.

In 1977, Lawrey reported the results of an investigation of habitats variously affected by coal strip mining. There were fewer fungal genera isolated from the disturbed areas and lower rates of respiration compared to undisturbed control sites. There was also a lower seasonal fluctuation in respiration in the disturbed areas, showing an increase of 16.6% (on average) compared to 62% in the undisturbed control, between January and April.

Cundell (1977) in a report on spent shale wastes and overburden from lignite strip-mines, and emphasised on the importance of micro-organisms in the re-establishment of a functioning ecosystem in strip-mined land.

Miller and Cameron (1978) reported on the microflora of 2 abandoned mines in the mid-western United States. They found the spoil materials unfavourable for survival and growth of soil organisms. Despite the establishment of pioneer populations of acidophilic fungi and some acid-tolerant algae, they recommended amelioration to raise the pH and to provide nutrients, especially nitrogen. It was suggested that biodegradable organic matter should also be added for its physical and biological effects. The authors pointed out that although 60 years had passed at 1 site since it had been abandoned, little colonisation, apart from at the periphery, had occurred. At this boundary, on the protected Northern treeline/refuse interface, mosses, lichens, and a diverse microflora had established, which should eventually lead to colonisation by macrophytes and crytogams, and increased nutrient cycling. The emphasis, then, was that there was a requirement to compress this successional process into a time scale where successful reclamation could be witnessed by legislators and the electorate.

In 1981, Miller and May reported on reclamation techniques suggested by Miller & Cameron 1978. After 5 years none of the reclamation treatments equalled an old field control in decomposition rates or microbial respiration. However, numbers of micro-organisms approached those in the control, but had much lower species diversity. This implies that the composition of the microbial community had become altered, to a population not capable of carrying out various stages of organic matter decomposition, but which may be dominated by 'zymogenous' bacteria capable of short-term rapid growth and lacking certain fungi, as shown in scores of 0.7 - 1.5 on Brillouin's Diversity Index for the disturbed areas as compared to 2.1 - 2.2 for the control plots.

Fresquez & Lindeman (1982) carried out a comparison between strip-mined areas restored with topsoil and with spoil. The objective was to see whether the latter developed a functional microbial community. A variety of amendments were made to the spoil, separately and in combination, including: inoculation with topsoil, addition of alfalfa hay and fertilizer, and addition of gamma-irradiated (and therefore sterile) sewage sludge. All of these were carried out as greenhouse pot experiments and were planted with *Bouteloua gracilis* and then replanted to *Atriplex canescens*. They found that topsoil inoculation alone did not increase numbers of bacteria, fungi, ammonia oxidizers (nitrifyers), or free-living nitrogen fixers. The dehydrogenase activity remained low, and the fungal species diversity narrow. However, both organic amendments led to an increase in all of the microbial parameters. This indicates that a readily available carbon source was more important in stimulating an active and diverse soil microflora than supplying a microbial inoculum.

Visser et al. (1983) investigated a prairie site in Alberta, Canada. A number of microbial factors were found to be significantly lower in the mined soil as compared to the control. These were: soil respiration, microbial biomass C, ATP, actinomycete numbers, hyphal lengths, and nitrogen-fixing potential. Bacterial numbers were, however, greater in the disturbed soil and dominated by coryneforms, whereas in the undisturbed control, *Bacillus* spp. and non-pigmented Gram-negative rods were also well represented. There was also a shift in the composition of the fungal species from 1 dominated by *Chrysosporium - Pseudogymnoascus* spp. and sterile dark forms, to 1 dominated by *Alternaria* spp., *Clasdosporium* spp., sterile dark forms, and yeasts; although little functional significance was attached to this shift by the authors. There were more *Penicillium* spp. occurring in the disturbed soils, and this was ascribed to them being among the most common air-borne saprophyticfungi, being able to grow on a wide variety of substrates and able to withstand a wide variety of environmental extremes such as low water potential and high temperatures. Visser and co-workers also found higher rates of decomposition of cellulose-filter papers placed on the soil surface in nylon mesh bags in the disturbed site as compared to the undisturbed control, indicating that there is potential, given the right conditions, for rapid loss of carbon from these disturbed soils. Supplying them with fertilizer-nitrogen could be precisely the wrong thing to do if long-term sustainability is the objective.

Visser (1985), also investigated use of amendments to mine spoils. In the case of bacterial numbers, actinomycete numbers total fungal mycelium and microbial biomass carbon, the order of increase in each case was NPK fertilizer < sewage sludge < peat. The peat also had the greatest effect in increasing total organic matter and nitrogen. Planting with either slender wheatgrass or white spruce also increased microbial biomass carbon after 27 months on the sub-alpine site and 39 months on the oil sand tailings. There were also effects on the rate of decomposition of a variety of litters, with Alsike clover leaves decomposing first, followed in order by, grass leaves, clover stems, and grass stems. This could be an advantage in the early stages of microbial recovery on mine spoils, as a constant supply of nutrients for primary production could be made available by the rapidly decomposing fraction, whereas the slowly decaying factor would perhaps contribute to the accumulation of stable organic matter. Wheat is very important as part of a management regime to ensure incorporation of this litter into the soil material, either mechanically or, preferably, by grazing organisms. Visser concluded by indicating the need for this type of management on restored sites, and that cognisance of differing rates of litter decomposition be made.

Finally, Fresquez et al. (1987) studied the effects of reclamation age, stockpiling of soil, and top soiling versus bare spoil on a number of enzyme activities. They found lower activities in non-topsoiled areas compared to topsoiled, with enzyme activities recovering in these topsoiled areas and peaking 1 to 2 years after reclamation. They concluded that topsoil was extremely useful in re-establishing soil processes after mining.

The relationship between soil microbial biomass and soil organic carbon on reclaimed sites has been demonstrated by Insam and Domsch (1988). In both restorations to agriculture and forestry, there was a decrease in the ratio of microbial carbon to total organic carbon with time, suggesting that the size of the microbial community increases at a slower rate than the increase in the total organic carbon pool. They considered, however, that even after 50 years asteady state had not been acheived. Hart et al (1989) supported this view, but added that other parameters, such as microbial biomass, soil respiration, and nitrogen mineralisation potential were equally usefull.

Harris and Birch (1989) demonstrated low dehydrogenase activity in areas restored after opencast coal mining in the UK. There were increases in activity with increasing age after restoration, and a highly significant correlation between soil water holding capacity and nitrfying potential.

Site status and ecosystem classification

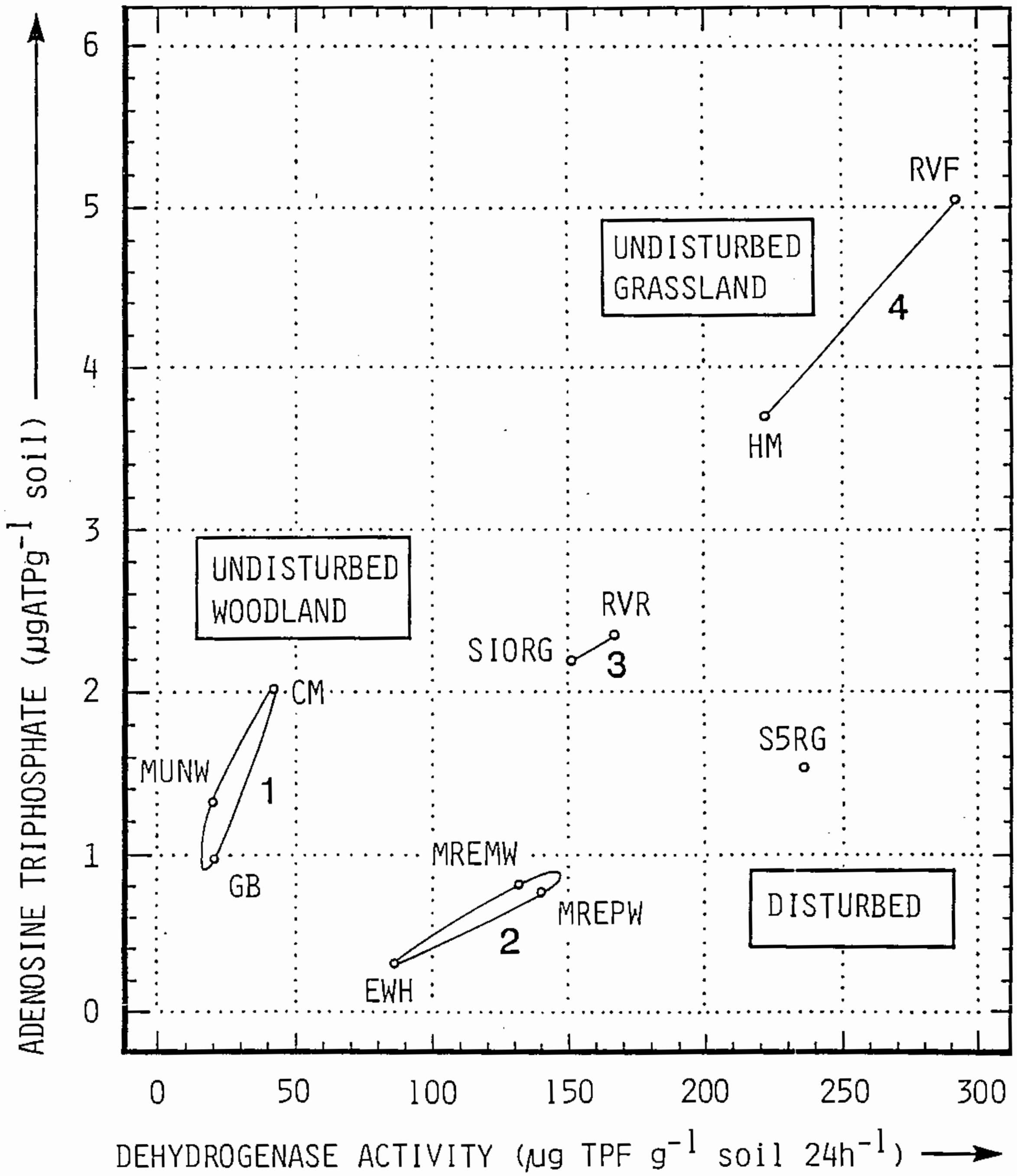
By drawing on these disparate studies, it is now possible to see emerging a means by which the assessment of restoration status and treatment success may be made in an objective way. There have been some steps taken in this direction, but again, no sytematic approach has been made. Harris and Birch (1990a) have suggested that the changes in the microbial community are so profound and consistent that they may be used as such an indicator of ecosystem status.

Hersemann and Temple (1978), in a study of mine spoils in Montana, were seeking an index of soil recovery. They came to the conclusion that adenosine-triphosphate content was the most satisfactory measure of soil microbial activity, as it correlated most often with the other parameters studied, namely respiration and phosphatase and pectinolyase activities. In a further piece of work concerning a study of retorted oil shales, Hersemann and Klein (1979) found a good correlation between soil dehydrogenase activity and numbers of fungi and bacteria; findings confirmed later by Fresquez & Lindeman (1982).

Insam and Domsch (1988) suggested that a microbial 'quotient' of microbial biomass carbon:total organic carbon could be used as a reliable guide to the success of reclamation efforts. This agrees with the work of Insam and Haselwandter (1989) which has demonstrated that a decrease in the respiration to biomass ratio accompanies ecosystem succession.

Recently, work in this laboratory has demonstrated the utility of soil dehydrogenase activity profiles in discriminating between different reclamation treatments (Harris and Birch, 1990b). This has been extended to include measurements of size of the microbial biomass as indicated by adenosine triphosphate (ATP) content of the soil. Bentham and Harris (1990) have reported the excellent discrimination between ecotypes achievable using this approach. In this study, by plotting biomass against dehydrogenase activivty for a number of sites, several distinct clusters have been formed (See Fig 1). Cluster 1 contains three woodland sites, Gernon Bushes (GB), Cranham Marsh (CM), and Morrells Wood (MUNW). Cluster 2 contains a breckland, or late dune succession scrub, East Writtenham Heath (EWH), and 2 mined, re-instated sites planted to wood (MREPW, MREMW), although these were originally grassland. Cluster 3 contains a low-productivity grassland on a Roding Valley Ridge (RVR), and a grassland re-instated from opencast mining some 10 years previously (S10RG). Cluster 4 contains 2 productive grasslands Hunsdon Mead (HM) and Roding Valley Floodplain (RVF), which have the highest activities and biomasses. There is 1 site isolated from the rest (S5RG) which was re-instated 5 years previously. This would appear to indicate 2 points: firstly, it would appear to be possible to provide an objective classification based on these parameters; secondly, there would appear to be recovery from mining demonstrated by the re-ordination of the disturbed site 10 years after reinstatement as compared to 5 years. Further to this, it seems probable that the development of the microbial community is directly linked, and may be responsible for, many terrestrial successional processes, adding weight to the arguments forwarded by Insam and Haselwandter (1989). This work is

Fig 1 Clusters of sites based on microbial biomass and activity



being extended by investigation of the ergosterol content of soils, in addition to the other parameters, to provide a 3 dimensional ordination.

Conclusion

The work reviewed here indicates that the microbial community plays an integral part in the recovery of ecosystems disturbed by opencast mining. Also, there is evidence that the microbial community may be manipulated to enhance ecosystem recovery. Further to this the soil microbial community may be used to classify both disturbed, semi-natural, and natural systems.

It is intended to extend this work on a wider geographical basis, and a wider range of ecotypes. The future of such investigations appears promising, and should provide evidence which will enable the formulation of both empirical and theoretical models of ecosystem succession in natural systems and in response to disturbance.

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