Restoration of soil function requires plants, arbuscular mycorrhizal fungi and organic matter

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Abstract
Insufficient topsoil often limits the establishment of native plants during restoration of mine sites. We address this problem by developing a suitable “capping topsoil” from coal mine overburden (spoil) for use at an open cut coal mine in Hunter Valley, NSW, Australia. The hierarchical model of aggregation served as the basis for the experiment. Plants with or without arbuscular mycorrhizal (AM) fungi were grown in 0, 6, 12 or 18% w/w of compost in spoil and placed in elongated tubes. Non-mycorrhizal plants in 18% compost amended spoil maximised water retention. Below 18% compost the presence of mycorrhizal fungi on roots of plants led to maximum water retention. A plateau in water retention was reached with the addition of between 6 and 12% compost in the mycorrhizal treatments, which is equivalent to 1.75 – 3.5% organic carbon in soil. Plants, AM fungi and organic matter were required to convert a massive mine spoil to a suitable “capping topsoil”.

Key Words
Volumetric water content, matric potential (Ψ_m), soil water curves.

Introduction
Extraction of subsurface materials to access mineral seams is a consequence of open cut mining. In Australia, these subsurface materials (overburden or spoil) require rehabilitation and restoration to varying degrees under the terms of the mining licence. The need for rehabilitation of these materials provides us with the opportunity to test many concepts of soil biology. Re-establishing native Australian plants directly into subsurface materials is rarely successful (Roe 1997). Spoil is often massive, lacking in organic carbon and soil microbiota, it can be saline, have adverse pH or be contaminated with metals (Dragovich and Patterson 1995). Spoil has poor water-holding capacity, few available minerals for plant growth and little resilience and resistance to perturbations (Fityus *et al.* 2008).

Ideally when rehabilitating spoil, fresh or stored topsoil from the A horizon is used to cap these subsurface materials (Harris *et al.* 1996). Sufficient topsoil for capping is rarely available through a combination of previous land use, erosion, contamination with weed seed and mixing of topsoil with subsoil. A supplementary source of topsoil, or a method to generate topsoil from existing materials would reduce the need to plant into bare spoil. The very attributes that make spoil a poor growing medium may be advantageous as the relatively inert and sterile properties of spoil can be exploited by utilising it as a parent material for development of a suitable “capping topsoil”.

Topsoil has a number of important attributes: organic matter and organic carbon contribute to good structure, enabling penetration by plant roots, minerals are available for plant growth, soil microbes and saprotrophic fungi contribute to nutrient cycling and arbuscular mycorrhizal (AM) fungi support diverse plant communities and contribute to soil aggregation (Tisdall and Oades 1982; van der Heiden 2002). Aggregation in topsoil arises as a consequence of the combined effect of fine roots, hyphae of mycorrhizal fungi and microbial mucilages that interact with the physical and chemical properties of soil in a hierarchical manner (model of Oades 1984; Tisdall 1991, 1994; Tisdall and Oades 1982). The model may be utilised to form the basis for constructing topsoil through addition of each of the proposed constituents required for aggregate formation. Changes in aggregation can then be inferred by quantifying soil water holding characteristics.

The aim of the work presented here was to test and quantify the contribution of the organic matter and mycorrhizal fungi to aggregation in mine spoil. It is part of a larger body of work examining the development of a “capping topsoil” from mine spoil.

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Methods

Compost (0, 6, 12 or 18% w/w) derived from bulk household and industrial garbage via the Bedminster process was mixed with spoil from a coal mine in the Hunter Valley, NSW, Australia and placed in elongated pots (final concentration 0, 1.7, 3.5, 5.2% organic carbon). The pots could be opened lengthwise to allow harvest of an intact core. Seedlings of *Dodonaea viscosa, Acacia decora* and *Lolium perenne* with or without eight different AM fungi were then transplanted into the amended spoil. Non-mycorrhizal plants were supplemented with phosphorous to give equal biomass within treatments. After six months in controlled growth conditions plants were harvested and soil water characteristics measured. Soil water characteristic curves were plotted from soil saturation to 1000 cmH_2O (98kPa) for each of the treatments. Soil aggregate stability by wet sieving and distribution of organic carbon in soil fractions were also determined but data are not presented here.

Results

Addition of organic matter alone decreased the bulk density of the soil in all treatments (data not shown) and increased the capacity to store water at any given matric potential (Ψ_m) at the 6 and 12% compost amendments (Figure 1A - C). Within a given compost treatment addition of non-mycorrhizal plants further increased water retention (Figure 1A – D) over compost alone. Addition of mycorrhizal plants maximised water retention at Ψ_m >50cmH_2O for the 0, 6 and 12% amendments (Figure 1A – D). Additions of compost beyond 12% did not increase water holding capacity of the soil under mycorrhizal plants. While addition of 18% compost conferred no additional water holding capacity for the compost alone and mycorrhizal plant treatments over the 12% amendments (Figure 1C – D), maximum water retention was found after adding 18% compost to the non-mycorrhizal plant treatment (Figure 1D).

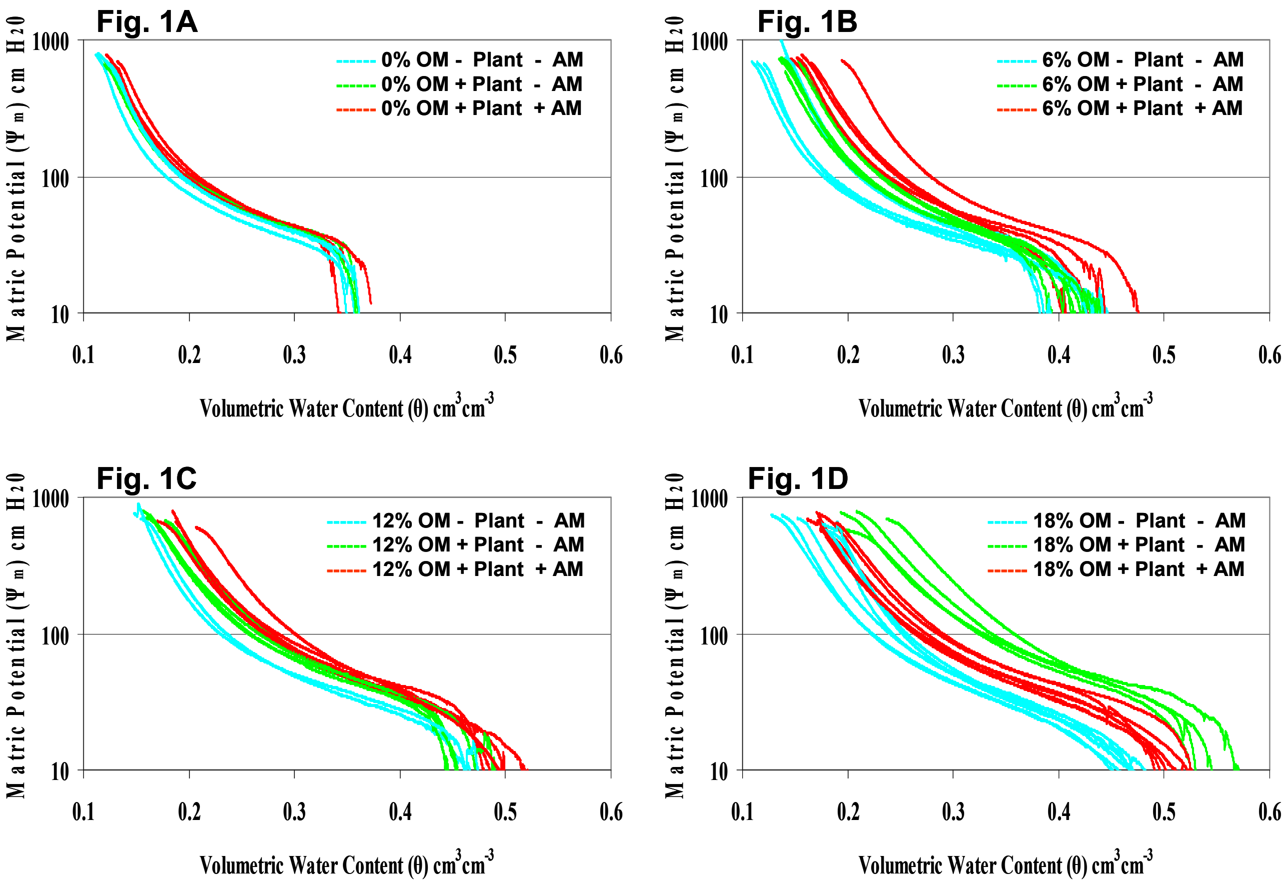

Figure 1. A - D Soil water characteristic curves 0, 6, 12, 18% organic matter (OM) [0, 1.7, 3.5, 5.2% organic carbon].

Discussion

Addition of organic matter, roots of plants and AM fungi each contributed to the development of the water holding characteristics of the spoil compost mix. The data from this experiment supported the view that the addition of organic matter decreases the bulk density of soil, and increases the quantity of water that is potentially held by the soil, regardless of the presence of plants. While addition of 18% compost maximised water retention, addition of compost alone is insufficient for forming a “capping topsoil” from mine spoil. Compost degrades over time, therefore a continuing carbon input to the soil is needed to sustain the carbon content. Additionally, the development of an interconnected pore structure, through the rearranging and enmeshing effect of root and AM fungal hyphae would provide a more attenuated pattern of water infiltration and extraction for plants (Auge *et al.* 2001; Tisdall and Oades 1982).

The addition of non-mycorrhizal plants to the compost amended spoil increased the water holding capacity beyond that of compost alone. The fine roots of plants (0.2 – 1 mm dia.) contribute to aggregation of soil (Miller and Jastrow 1990). Non-mycorrhizal roots may also contribute root exudates which determine the community structure of saprotrophic microbiota in the rhizosphere (Marschner and Baumann 2003) possibly increasing adhesion between soil particles (Tisdall and Oades 1982). Below 18% compost the presence of mycorrhizal fungi on roots of plants led to maximum water retention in amended mine spoil. A plateau in water retention appeared to have been reached with the addition of between 6 and 12% compost, which is equivalent to 1.75 – 3.5% organic carbon in soil. The data from this experiment provides further evidence for the contribution of AM fungi to the creation of soil structure and greatly expands existing knowledge on their influence of soil water characteristics (Auge *et al.* 2001). The complete mechanism is unclear but is likely to include the development of macro-aggregates following enmeshment of micro-aggregates. The hyphae will also express exudates, adding to the energy supporting the microbial community.

A self-sustaining soil would meet the desired characteristics of a “capping topsoil”. Soil structure will be maintained beyond the six months of this experiment if plants and mycorrhizal fungi continue growth and development, as is likely in the field. Active growth of both will contribute to deposition of organic exudates and debris. Mine spoil clearly requires initial addition of organic matter if formation of a “capping topsoil” suitable to support native plant growth is the goal of restoration. In the field the addition of 18% compost to spoil is impractical for economic reasons. Below 18% compost the presence of mycorrhizal fungi on roots of plants led to maximum water retention in amended mine spoil, and we suggest that for field applications, planting mycorrhizal seedlings in 6 – 12% compost in spoil is a practical approach. The locally supported content of organic carbon in restored field soils is uncertain at this time. However long-term field studies at the mine site indicate carbon storage in restored spoil of between 2 and 3% (Nussbaumer and Cole unpublished data) which is the addition of between 6 and 12% compost. These analyses will be tested in the field.

Several questions remain: while we deliberately introduced AM fungi to the amended spoil, many other microbes would have colonised the soil mixtures. The identification and contribution made by each of these and other groups of microbes requires further examination. At the very least, saprotrophic microbes will contribute to the turnover of organic matter (Holland and Coleman 1987) and possibly to the development of micro-aggregates through the exudation of mucilage. The role of microbial mucilage in soil aggregation is poorly understood. Interactions between saprotrophic and symbiotic microbes are also complex and careful examination is required to determine their degree of contribution and the importance of their interactions. In addition, whether complex AM fungal communities support complex plant communities on the capping topsoil requires more careful exploration (van der Heiden 2002). Planting alone in mine spoil frequently fails to provide satisfactory vegetation (Carter and Ungar 2002). Addition of mycorrhizal plants alone did not improve the establishment of a capping topsoil nor did the addition of compost without plants. The development of realistic microbially complex capping topsoil clearly requires addition of organic matter, plants and their attendant AM fungi.

Conclusion

Successful rehabilitation and restoration of mine sites is limited by insufficient topsoil. The hierarchical theory of aggregation served as a useful tool for examining the development of structure in a massive mine spoil. Addition of organic matter, plants and their AM fungi resulted in the development of a “capping topsoil” within six months as indicated by soil water characteristics.

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