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RESTORATION OF SOIL FUNCTION REQUIRES PLANTS, ARBUSCULAR MYCORRHIZAL FUNGI AND ORGANIC MATTER

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Abstract: The hierarchical model of aggregation proposes that soil aggregation is due to a stepwise hierarchy of processes. The model is normally experimentally tested using topsoil by disrupting and dispersing aggregates and characterising the end products, that is, a top down approach. We present a series of experiments testing the model using a resilience approach, attempting to create an aggregated soil by adding the required constituents to a massive soil, a bottom up approach. Plants, with or without 8 arbuscular mycorrhizal fungi were grown for 6 months in sieved mine spoil amended with up to 18% organic matter. The soils were examined for aggregation, water holding capacity and carbon content. The data broadly support the hierarchical model. Maximisation of functional complexity as indicated by water retention curves and particle mean weight diameter required approximately 12% organic matter (3% organic carbon), plants and the presence of AM fungi. We conclude that successful remediation of a massive soil requires consideration of the complexity of the interaction between plant, AM fungus and organic matter, and that the hierarchical model of aggregation serves as a useful tool in soil restoration.
Key words: Carbon, Hierarchical model, Mean weight diameter, Soil aggregate, Water retention

1. INTRODUCTION

The conceptual model proposed by Tisdall and Oades (1982) and subsequently refined (Oades, 1984; Tisdall, 1991; Miller, and Jastrow, J.D., 1992; Tisdall, 1994) proposes that soil aggregation is due to a stepwise hierarchy of mechanisms. Particles <2 µm are held together mainly through electrical and chemical forces. These particles in turn are bound into aggregates 2 – 20 µm diameter by degraded products of microbes and plants, and contain cells of microbes and clay. Fungal hyphae especially of arbuscular mycorrhizal (AM) fungi bind these <20 µm aggregates into micro-aggregates 20 – 250 µm. Finally fine plant roots and fungal hyphae bind these micro-aggregates into macro-aggregates >250 µm (Oades and Waters, 1991). This process is commonly referred to as the "hierarchical model of aggregation". The model has widespread acceptance and can be applied to many but not all soils (Oades and Waters, 1991). The model is normally experimentally tested using soils with well developed structure by disrupting and dispersing aggregates and characterising the end products, that is, a top down approach (Miller and Jastrow, 1990; Six et al., 2000). A resilience approach, whereby the recreation of an aggregated soil from its constituent components is not normally used to test the model. Restoration of top soil from massive materials such as mine spoil requires the application of the hierarchical model from the bottom up. It will require the formation of water stable aggregates, a porous structure which allows for infiltration and retention of water in complex pores, and a return of organic carbon to the core of micro-aggregates (von Lützow et al., 2006). The model identifies the important components associated with aggregate formation; AM fungi, organic matter, particulate inorganic materials, microbial mucilages and plants. Thus the hierarchical model may serve as a useful tool in identifying factors necessary for restoration of a massive soil.

The aim of the work presented here was to test the contribution of the various constituents to aggregation, with the goal of restoring and a developing functional soil from mine spoil.

2. MATERIAL AND METHODS

Compost (0, 6, 12 or 18% w/w), derived from bulk household and industrial garbage via the Bedminster process, was mixed with autoclaved spoil from a coal mine in the Hunter Valley, NSW, Australia, and placed in elongated pots (final concentration 0.1%, 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 8 different AM fungi were then transplanted into the amended spoil. Plants without AM fungi were fertilised with phosphorous to give similar above ground biomass within each compost treatment. After 6 months in controlled growth conditions plants were harvested and soil water characteristics curves (ku-pF apparatus, UGT GmbH, Munich, Germany & WP4-T Dewpoint Meter, Decagon Devices Inc., Pullman, Washington, USA), soil aggregate stability by wet sieving, modified from Yoder (1936) and distribution of organic carbon in soil fractions (VarioMAX CNS analyzer, Elementar Analysensysteme GmbH, Hanau, Germany) were determined. Aggregate fraction size was converted to mean weight diameter (Youker and McGuinness, 1957).

3. RESULTS AND DISCUSSION

The addition of organic matter (OM) alone increased mean weight diameter (MWD) partly due to the larger particle size distribution (data not shown) of the OM compared to spoil (Table 1).

Addition of plants with or without AM fungi had no effect on MWD when planted into spoil with no OM amendments. With addition of 6% OM the plants with AM fungi significantly increased MWD over both the control and plant alone treatments. At 12% OM the plants alone significantly reduced MWD compared to the control and plants with AM fungi. At 18% OM amendment MWD was greatest in the control.

Content of carbon in the micro-aggregate fraction (53 – 250 µm) significantly declined when plants with and without AM fungi were present in unamended spoil (Table 2). At 6% OM amendment, plants without AM fungi significantly increased carbon in micro-aggregates when compared to plants with AM fungi. Plants with AM fungi significantly increased carbon content in micro-aggregates compared to the control at 12% OM. At 18% OM carbon content significantly increased when the plants were grown with and without AM fungi. The carbon content of macro-aggregates (250 – 710 µm) was similar across all treatments except under mycorrhizal plants growing in 18% OM where the carbon content was significantly increased (Table 2).

Increasing OM alone increased soil capacity to store water (Table 3). Soil water retention curves revealed significant differences between treatments (-40kPa data presented). The introduction of plants with AM fungi into unamended spoil caused a small but significant increase in soil water content (θ) at -40kPa compared to plants alone and the control. At 6% and 12% OM amendments, plants without AM significantly increased θ compared to the control, while plants with AM fungi had significantly greater θ than the control or plants alone. At 18% OM non-mycorrhizal plants had significantly larger θ compared to both the control and mycorrhizal plants.

Table 1. Mean weight diameter of soil after soaking for 5 minutes and sieving for 8 minutes at 30rpm with 2.5cm vertical displacement

	Mean Weight Diameter (µm)		
%OM	No Plants	Plants -AM	Plants +AM
0	489^{a}	499^{a}	497^{a}
6	605^{a}	612^{a}	715^{b}
12	958^{b}	713^{a}	962^{b}
18	1053^{b}	764^{a}	869^{a}

Values across rows with different letters indicate significance at P<0.05

Table 2. Total carbon in micro-aggregate (53 – 250 µm) and macro-aggregate (250 – 710 µm) fraction sizes

	% Carbon					
	53 - 250µm			250 - 710µm		
%OM	No Plants	Plants -AM	Plants +AM	No Plants	Plants -AM	Plants +AM
0	1.57^{b}	1.47^{a}	1.45^{a}	1.75^{a}	1.65^{a}	1.59^{a}
6	1.77^{ab}	1.88^{b}	1.67^{a}	1.88^{a}	2.08^{a}	1.95^{a}
12	2.22^{a}	2.46^{ab}	2.55^{b}	2.44^{a}	2.88^{a}	2.92^{a}
18	2.69^{a}	3.48^{b}	3.29^{b}	3.24^{a}	3.79^{ab}	4.04^{b}

Values across rows with different letters indicate significance at P<0.05 within each fraction size

Table 3. Volumetric Water Content of Soil (θ) at -40kPa

	Water Content at -40kPa (θ)		
%OM	No Plants	Plants -AM	Plants +AM
0	.132^{a}	.136^{a}	.143^{b}
6	.140^{a}	.160^{b}	.182^{c}
12	.163^{a}	.189^{b}	.204^{c}
18	.182^{a}	.261^{b}	.192^{a}

Values across rows with different letters indicate significance at P<0.05

The hierarchical model indicates a contribution by organic matter, the roots of plants and AM fungi to the development of soil aggregation and its corollary, soil water holding capacity. The model has a number of implicit implications which our data broadly supports, namely; decreasing organic matter, lack of fungal hyphae (especially AM fungi) or lack of plant roots are associated with reduced MWD. Macro-aggregates tend to have more carbon than micro-aggregates.

While this experiment added AM fungi, exposure of soil over 6 months will inevitably allow colonisation of the soil by saprotrophic fungi. Saprotrophic fungi may bind and stabilise soil particles into water stable aggregates (Caesar-TonThat and Cochran, 2001). The contribution of these fungi to the outcomes of this experiment remains unclear and is being tested in further experiments. Mine spoil was used as a model massive soil. The applicability of these data to other massive and poorly structured soils needs to be determined.

Refinements to the hierarchical model (Oades, J.M., 1984; Beare et al., 1994) suggest individual macro-aggregates may form around particulate organic matter. Micro-aggregates are formed at the centre of the macro-aggregate as this organic matter decays. This sub-process may explain the apparent anomaly of the 12% and 18% OM controls having similar or greater MWD to the other treatments. The added OM would have partially decayed in the soil through the actions of saprotrophic microorganisms and chemical processes. Soil is a complex system and multiple methods of analysis are needed to indicate the various interactions.

MWD was significantly higher in the mycorrhizal plant treatment than plants alone when spoil was amended with 6 and 12% OM. The ability of plant roots to bind aggregates is reduced without AM fungi (Thomas et al., 1993). Indeed, plant exudate profiles in mycorrhizal and non-mycorrhizal plants differ, perhaps leading to quite different communities of saprotrophic organisms interacting with available organic materials (Marschner and Baumann, 2003). Interpretation of soil carbon analysis was more complex. In broad terms, addition of organic matter increased carbon held in the spoil. With increasing organic matter, carbon held in micro-aggregates increased, indicating greater storage of carbon with planted and mycorrhizal planted treatments. Further tests are necessary to determine whether this stored carbon is stabilized and protected from degradation, as carbon is more likely to be sustained in micro-aggregates (von Lützow et al., 2006).

The water-holding capacity of a soil is determined by the complexity and distribution of pores among water-stable aggregates. The data indicate that additions of organic matter to mine spoil increased water retention, and that the addition of plants and mycorrhizal fungi maximised water-holding capacity. Mycorrhizal plants had a greater impact than plants alone, and both were more effective than simple addition of organic matter.

The development of soil structure over 6 months with the addition of compost indicates the establishment of a system that appears to maintain its characteristics provided plant roots and AM fungi remain active. While this assertion requires more careful testing, this self-sustaining soil would meet the structural characteristics of topsoil. The presence of roots alone was less effective than roots plus AM fungi in retaining soil water. This suggests that the fungi are contributing to the rearrangement and aggregation of particles and organic matter in soil, possibly through exploration of the soil phase by hyphae. However, soil is a dynamic and complex system.

Teasing apart the contributors to these processes will require further tests in quite different soils, and environments. In this system additions of OM beyond 12% are unlikely to be of benefit in restoration of soil processes. Different systems may have quite different requirements for enhancing the various soil functions.

Many factors contribute to soil function. Some of these functions have been examined in the hierarchical model of soil aggregation. This research has tested the model by aggregating mine spoil using a wide range of organic matter, and the presence of plants alone or plants with arbuscular mycorrhizal fungi. The hierarchical model is supported by this bottom up approach. Further factors that now need to be considered are; the role of saprotrophic fungi, the quantity of mycelium, the diversity of plant communities and the quality and protection of carbon in micro-aggregates.

4. CONCLUSION

The hierarchical theory of aggregation serves as a useful tool for rehabilitating massive soils utilising a bottom up approach. Maximisation of functional complexity of a soil derived from coal mine spoil from Hunter Valley, NSW Australia required approximately 12% organic matter (3% organic carbon), plants and the presence of AM fungi. Successful remediation of soil requires consideration of the complexity of the plant/AM fungus/soil organic matter interaction in each case.

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