

Soil Health and Related Ecosystem Services in Organic Agriculture

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Abstract

Soil health is dependent upon complex bio-physical and bio-chemical processes which interact in space and time. Microorganisms and fauna in soil comprise highly diverse and dynamic communities that contribute, over either short or long time frames, to the transformation of geological minerals and release of essential nutrients for plant growth. Certified organic soil management practices generally restrict the use of chemically-processed highly soluble plant nutrients, leading to dependence on nutrient sources that require microbial transformation of poorly soluble geological minerals. Consequently, slow release of nutrients controls their rate of uptake by plants and associated plant physiological processes. Microbial and faunal interactions influence soil structure at various scales, within and between crystalline mineral grains, creating complex soil pore networks that further influence soil function, including the nutrient release and uptake by roots. The incorporation of organic matter into soil, as either manure or compost in organic farming systems is controlled to avoid excessive release of soluble nutrients such as nitrogen and phosphorus, while simultaneously contributing an essential source of carbon for growth and activity of soil organisms. The interdependence of many soil physical and chemical processes contributing to soil health is strongly linked to activities of the organisms living in soil as well as to root structure and function. Capitalizing on these contributions to soil health cannot be achieved without holistic, multiscale approaches to nutrient management, an understanding of interactions between carbon pools, mineral complexes and soil mineralogy, and detailed examination of farm nutrient budgets.

Keywords: soil biological fertility, mineral nutrient sources, organic matter, soil biodiversity, local knowledge

1. Introduction

Organic agricultural practices are underpinned by soil biological processes that are influential in the supply of nutrients to plants as well as to the creation of beneficial soil structural conditions for plant growth (Mader et al., 2002; Bhaduria & Sazena, 2010). Both bio-physical and bio-chemical processes are central to the effectiveness of organic productive systems (Gomiero et al., 2011). Provision of an adequate supply of nutrients in certified organic farming systems can be challenging if they depend on sources of low solubility (Quilty & Cattle, 2011). Furthermore, the avoidance of loss of nutrients into the surrounding environment, including loss to groundwater, is also a high priority for organic systems (Askegaard et al., 2011). The effectiveness of use of nutrients in organic farming systems depends on the rate of cycling of nutrients from both organic matter and allowable minerals, which differ in magnitude according to the soil's inherent fertility (Heitkamp et al., 2011) and mineralogical composition (van Straaten, 2002). Globally, soils used for organic agriculture range from deep, highly fertile soils to shallow, highly weathered and nutrient depleted soils (Chivenge et al., 2011). The nutrient amendments required in organic agriculture therefore vary considerably depending on the local soil and environmental conditions, and potential level of productivity at the location of the farm (French & Schultz, 1984).

1.1 Soil Biological Fertility

A major component of soil fertility in organic farming systems depends on biological processes that sit within the framework of organic certification (Fließbach et al., 2007). Soil biological fertility has been defined as “*the capacity of organisms living in soil (microorganisms, fauna and roots) to contribute to the nutritional requirements of plants and foraging animals for productivity, reproduction and quality (considered in terms of*

human and animal wellbeing) while maintaining biological processes that contribute positively to the physical and chemical state of soil.” (Abbott & Murphy, 2003). Organic certification emphasises agricultural management practices that support soil biological processes (Gomiero et al., 2011) contributing significantly to the nutritional status of soil. Supplying adequate levels of nutrients for plant growth in organic systems is complex where it depends on soil processes for nutrient release. Excessive nutrient concentrations in the soil solution can arise if high quantities of manure are added to soil (Foissy et al., 2013). Therefore, this needs to be managed carefully to avoid nutrient loss. Although soil structure is largely dependent on the parent material, enhancement of biological processes can improve soil aggregation (Pulleman et al., 2005; Six et al., 2004), access to water (Augé, 2001), and reduce hard setting when combined with an appropriate quantity of organic matter (Djajadi et al., 2012).

Agricultural practices such as tillage, crop rotation and organic amendments significantly influence soil chemical and physical fertility (Birkhofer et al., 2008). They alter the rate of release of nutrients for plant uptake and growth of roots leading to both direct and indirect effects on plant production and delivery of ecosystem services (Sandhu et al., 2010). Tillage can hasten soil structure decline (Conceicao et al., 2013) but it is difficult to avoid in organic systems although no-till organic options are being explored (Carr et al., 2011). There is evidence that negative effects of tillage on some beneficial biological processes such as the accumulation of soil microbial biomass, may be less marked in tilled organic systems compared with conventionally tilled systems (Larsen et al., 2014).

In agricultural systems where large quantities of relatively soluble synthetic fertilisers are used, some soil biological processes (such as nitrogen fixation and colonisation of roots by arbuscular mycorrhizal fungi) can be over-ridden, and their contributions may not be fully realised for agricultural production (Richardson et al., 2011) or efficient resource use (Rice et al., 2002). On the other hand, the slow rate of release of nutrients from recalcitrant sources of minerals (Manning, 2008, 2010) or from plant residues (Damon et al., 2014) may restrict plant production in organic systems compared with conventional agricultural systems. While this is commonly viewed as a deficiency of organic systems, alignment of productivity at a particular site to that which is sustainable in the longer term, based on lower risk potential (Tiedemann & Latacz-Lohmann, 2013) is fundamental to organic agriculture. In some environments, organic production may lead to ‘mining’ or reduction of existing nutrient resources (Romanya & Rovira, 2009), some of which may have been added to soil prior to organic certification. Soil fertility in organic farming systems is complex, and needs to be considered locally according to (i) existing and previous soil conditions, (ii) environmental conditions, including environmental change, (iii) plant requirements at different stages of their growth cycles, (iv) quantify of nutrients removed in grain or consumption of forage, (v) rotational sequences, (vi) soil disturbance, and (vi) economic models employed by the farmer.

1.2 Soil Biodiversity

Soil biodiversity is important in effective management of organic farming systems for chemical and physical fertility. Soil organisms need to be managed to ensure they contribute at optimal levels within and between seasons. For many soil organisms, their collective contributions depend on the form and quantity of organic matter in the soil and on environmental conditions that occur at the scale of soil aggregates, roots and soil pores (Rillig & Mummey, 2006). For other organisms, such as those that are involved in nitrification (de Gannes et al., 2014), indirect relationships with mineralisation of organic matter can influence nitrogen cycling, including nitrogen loss. They may be significantly influenced by soil chemical conditions such as pH (Bramley and White 1990) and soil physical conditions such as compaction and water-logging (Engelaar et al., 2000).

The diversity of soil organisms varies within and among soils managed according to the guidelines of organic certification (Hartmann et al., 2014). Furthermore, there are dynamics in activity and relative abundance of soil organisms in response to availability of substrate or following nutrient application. The extreme diversity of soil organisms builds redundancy in function (Wolters, 2001; Chaer et al., 2009). Long-term reduction in organic inputs into soil can reduce the capacity of the community to mineralise some recalcitrant organic carbon fractions in soil (Paterson et al., 2011) and harsh conditions can minimise some functions (Liebich et al., 2007). It is likely that there are threshold levels of relative abundance and/or diversity for optimal function for some communities of soil organisms (Philippot et al., 2014). Soil biodiversity varies according to soil type, location and management practices (Paterson et al., 2011). However, the potential impact of changes in diversity, dominance and abundance of communities of soil organisms may or may not affect soil conditions for plant growth.

In addition to differences in the diversity, relative abundance and biomass of organisms in soil, there are

considerable differences in their function (McGuire & Treseder, 2010). It is not easy to equate diversity patterns of soil microbial communities, levels of microbial biomass, or levels of soil microbial respiration to 'ideal' soil conditions for their growth because temporal dynamics in suitable carbon substrate (Hoyle & Murphy, 2011) or water deficit (Kakumanu & Williams, 2014) can influence their abundance and activity. Most organisms go through periods of inactivity because local conditions are temporarily unsuitable (Bardgett, 2002). There is evidence of increased diversity of some groups of soil organisms with conversion to organic farming practices. For example, the diversity of arbuscular mycorrhizal fungi was higher in organic fields, and similar to that of natural grassland, compared with conventional agricultural management (Verbruggen et al., 2010). In a comprehensive comparison of soil microbial diversity in the long term DOK Trial in Switzerland, diversity of both soil bacteria and fungi were markedly affected by organic farming practices (Hartmann et al., 2014). Five farming systems were examined, three of which had organic management. Application of nutrients had a larger impact on soil microbial communities compared with plant protection practices used. There were distinct microbial communities in the different farming systems and these differences were less affected by spatial heterogeneity or temporal change. The higher resolution of microbial communities identified in this study compared with previous studies at the same site showed that, most likely the application of farm yard manure had a significant influence on microbial community structure (Hartmann et al., 2014). The differences between microbial communities in the organic and conventionally managed land in this study were largely attributed to the form and amount of organic fertiliser. Hartmann et al. (2014) noted that despite the higher diversity of bacteria and fungi in organically managed soil, the functional significance of this finding is not well understood. In this case, the higher diversity was closely associated with application of organic fertiliser, rather than other organic practices such as integrated pest management. Differences in tillage practice were not specifically investigated here, but they could also be expected to have significant effects on microbial community structure in organic farming systems (Yang et al., 2013).

Levels of soil microbial biomass and gas fluxes in organic farming systems can be higher than in conventional systems and are commonly linked to levels of organic matter (Chirinda et al., 2010). However, soils differ widely in their potential to protect organic matter from mineralisation (Zimmermann et al., 2012). This in turn reflects on differences in microbial activity associated with mineralisation. Therefore, although the level of microbial activity in soil may be higher in organic than in conventionally managed farming systems (Gunapala & Scow, 1998), it may not be indicative of plant productivity because many factors combine to define achievable levels of plant yield. On the other hand, higher microbial activity may contribute to greater loss of nutrients from soil for some combinations of organic management practices, including use of cover crops and tillage.

Differences in clay, loam or sand content of soil influence thresholds for 'ideal' levels of microbial biomass but benchmarks also depend on local conditions. A sandy soil may temporarily be highly biologically active leading to rapid depletion of organic matter because the organic resources are not well protected in soils with low structural stability. In contrast, a more clayey soil may display less marked peaks and troughs in microbial respiration than a sandy soil in response to mineralisation of organic matter because of its higher structural stability and greater capacity to protect organic matter (Djajadi et al., 2012). Overall, 'effective biological functioning' of soils under organic management differs widely according to soil type and location in the landscape, plant production practices, irrigation practices and nutrient inputs (Chirinda et al., 2010). Local benchmarking according to soil type, management practice and environmental condition is necessary because of the complexity of relationships between microbial activity, microbial diversity and plant response.

1.3 Bio-Physical and Bio-Chemical Processes

Bio-physical processes underlie structural configurations in soil and influence soil aggregation (Rillig & Mummey, 2006), mineral dissolution (DeJong et al., 2013), water and nutrient access by roots (Dunbabin et al. 2002), and resilience to intermittent drought stress (Thierfelder & Wall, 2010). Furthermore, these processes occur in the same or overlapping timeframes and some organisms may simultaneously be involved in more than one process (Moore, 1994). Soil organisms involved in biological perturbation contribute to mineralisation of organic matter, while soil enzymes may be involved in mineralisation of organic matter or dissolution of geological minerals (Burns et al., 2013). Soil amendment with manure, commonly used in some but not all organic agricultural systems, alters both the soil physical and chemical environment. This has flow-on effects to biological processes in soil, and complex bio-physical and bio-chemical processes are also involved (Rillig & Mummey, 2006; Six et al., 2004). Arbuscular mycorrhizal fungi (Cavagnaro et al., 2012) are examples of a community of soil organisms that cross boundaries of chemical and physical fertility by contributing to nutrient use efficiency, soil structural development, access to water, and resistance to plant disease. Some of the bacteria and fungi involved in nutrient cycling also contribute to stabilising soil aggregates (Six et al., 2004). It is difficult

to quantify biological contributions to each of these process separately, and to identify their specific economic value (Abbott & Lumley, 2014).

Organic management practices seek to maximise contributions from specific groups of soil organisms such as those involved in symbiotic nitrogen fixation, microbial facilitation of nutrient uptake at root surfaces (Verbruggen et al., 2010), and disease suppression (Benitez et al., 2007). These functions are all influenced by the physical and chemical characteristics of soil to some extent. Earthworms have particularly important roles in altering soil structure (Versteegh et al., 2014) as well as in nutrient cycling, and while their contributions may be enhanced in organically managed systems, other considerations such as the length of time in pasture or cropping can override effects of organic compared with conventional management practices on their abundance (Pulleman et al., 2005). Selectivity in incorporation of organic matter into soil by earthworms further highlights the complexity of interactions between mineralisation and soil structural contributions of earthworms in organic farming systems (Pulleman et al., 2005). Organic practices can foster contributions of both mesofauna and macrofauna to soil ecosystem functioning (Dominguez et al., 2014). Furthermore, the abundance and diversity of larger soil fauna may be less influenced by organic farming practices than by conventional management practices based on observations of species richness (Postma-Blaaaw et al., 2010). In organic systems, effective functioning of soil communities may reduce disease risk associated with increased suppressiveness of soils (Yogef et al., 2011). Plant health is a complex issue (Doring et al., 2011), especially in the context of organic farming because the emphasis is not on completely eradicating pathogens or pests; maintaining soil ecosystem function is of high priority for building resilience against the development of disease or damage caused by pests.

2. Certification Requirements Define Nutrient Inputs

2.1 Examples of Allowable Mineral Sources of Nutrients

Certification requirements define allowable nutrient sources for use in organic farming systems, and include poorly soluble forms of minerals, including rock phosphate, dolomite, lime and milled silicate rocks ('rock dust') as well as a range of sources of organic matter including compost. Certification requirements restrict use of the most soluble forms of both phosphorus and potassium (permitting mined potash salts according to circumstances), so alternative sources need to be used. Allowable sources of phosphorus differ in solubility over time and in relation to soil pH (Manning, 2008). Other allowable rock-based nutrient sources, including feldspars, feldspathoids and micas, can provide a range of elements such as potassium, calcium, sodium and silica, with traces of other elements, but all are low in solubility (Harley & Gilkes, 2000). Potassium can be supplied from potassium silicate minerals containing feldspar, nepheline and mica (Manning, 2012). It is released during weathering of the rock-forming minerals, especially micas (Mohammed et al., 2014). Weathering processes are slow but depending on climate and soil properties, the quantities required for plant growth may be delivered during the season. Additionally, micas and clay minerals influence cation exchange reactions (Manning, 2012).

The rate of release of nutrients from mineral resources depends on the mineral crystal structure as well as the concentration of nutrient, and the rate of release may be increased through involvement of microorganisms by addition of composted organic matter (Manning et al., 2013). Clay minerals can form complex associations with organic matter that can influence its stability (Jundaluang et al., 2013). Humus adsorbed on clay minerals can affect the rate of release of potassium and silica when exposed to organic acids (Datta et al., 2009). For humus-depleted clay, an initial release of potassium triggered further release of potassium (Datta et al., 2009). This study showed that clay-humus complexes can restrict the release of potassium. However, there is also potential for microbial processes to increase mineral dissolution (DeJong et al., 2013).

It has been shown that individual minerals in close proximity on rock surfaces exposed to the environment can have distinctive bacterial communities (Hutchens et al., 2010). Specific bacterial isolates were found on feldspar, quartz and muscovite in the rocks studied. Fungal communities tended not to display the same level of specificity as bacterial communities (Gleeson et al., 2010). While these studies have been conducted on exposed rock surfaces, different forms of minerals were shown to influence microbial community structure when they are introduced into soil (Carson et al., 2009). In this study, mica, basalt and rock phosphate were incubated separately in soil with or without a legume. Bacterial communities on individual mineral fragments differed from those in the surrounding soil. Thus, addition of poorly soluble minerals to soil could create microhabitats and contribute to spatial variation in bacterial communities (Carson et al., 2009); this in turn may support highly diverse microbial communities in organic farming systems with specific rock-mineralising capabilities.

2.2 Examples of Sources of Nutrients From Organic Matter

Organic matter is the primary source of many nutrients in organic farming systems (Heitkamop et al., 2011). Retention of organic matter is essential for good management and provides other benefits to soil conditions for

plant growth. Microbial processes are involved in effective recovery of nutrients from manure and composted organic matter resulting in the release of essential plant nutrients during interactions with soil fauna, including earthworms (Bhadoria & Sazena, 2010). Higher levels of microbial activity in soil under organic management may not necessarily lead to increased access to stable forms of phosphorus in organic matter (Keller et al., 2012). Re-use of organic 'wastes' (e.g. manure), when permitted by organic certification, can contribute valuable sources of nutrients in organic farming systems (Heitkamp et al., 2011; Fließbach et al., 2007). Combinations of composted organic matter and clay-based minerals can increase the rate of release of nutrients from rock minerals (Manning et al., 2013).

Stable isotope tracing is used to identify relationships between the nitrogen, phosphorus and carbon cycles in soil by tracking nutrients through the complex pathways (Dungait et al., 2012a). Near edge X-ray fine structure spectroscopy and scanning transmission X-ray microscopy have potential to provide new opportunities for three-dimensional investigation of molecules in soil (Schmidt et al., 2011). There are also opportunities for clarification of "recalcitrant" vs "protected" organic matter (Dungait et al., 2012b), and for identifying the roles of different microbial communities in connected and disconnected soil pores (Carson et al., 2010).

3. Delivery of Ecosystem Services in Organic Farming Systems

Organic farming systems have potential to deliver a wide range of ecosystem services associated with soil health if they (i) increase efficiency in use of nutrients from less soluble sources (Manning, 2012), (ii) minimise loss of nutrients to ground and surface water bodies (Ekholm et al., 2005), (iii) release nutrients according to plant requirement (Damon et al., 2014), (iv) budget for replacement of nutrients according to their removal (Dalgaard et al., 2002), (v) reduce the susceptibility of plants to disease (Postma et al., 2008), (vi) reduce erosion by minimising tillage (Peigné et al., 2014), and (vii) increase access to water during periods of low-rainfall (Thierfelder & Wall, 2010). Use of comprehensive whole-farm nutrient budgets (Dalgaard et al., 2002) increases the likelihood of maximising nutrient use efficiency. Successful delivery of ecosystem services attributed to organic management may be constrained by environmental conditions and soil type (including inherent levels of soil fertility based on the source of parent rock).

Interestingly, Adl et al. (2011) concluded that the conventional agricultural practice of using pesticides can provide benefits to organic systems if they lower the threshold of disease locally. For example, if the ratio of the area of organic to adjacent conventional farmland is kept below a threshold level, the pest population can remain low. If the area ratio exceeds the threshold, the pest population can increase in the organically managed area, increasing risk to the conventionally managed area. In this case, the area under organic agriculture could be a pest reservoir.

Organic agricultural practices related to soil health provide a model for addressing the challenging issue of maximizing beneficial soil biological processes in agriculture generally, not just in organic systems. Local conditions will constrain the extent to which biological processes can proceed effectively. Furthermore, the biological status of soil is dynamic, and differs in magnitude according to season, soil type and management history (Zelenev et al., 2006; Hoyle & Murphy, 2011; Le Guillou et al., 2012). Benchmarks are not easily attained for any of the soil parameters that could be measured because of this variability. An important aspect of organic systems is the simultaneous focus on phosphorus as well as nitrogen cycles, in contrast to many current conventional practices, but attention also needs to focus on potassium. Finally, organic systems are practiced on soils that vary widely in structure and inherent fertility, and they differ in their exposure to climatic and environmental conditions. Therefore, caution is required in generalising about issues related to soil health in organic farming systems because on-farm management efficiency differs. Nevertheless, there is a continual requirement to minimise detrimental environmental impacts, maximize nutrient use efficiency, re-use waste, and manage the soil for sustainable agricultural production.

4. Conclusion

Organic farming practices have the potential to contribute significantly to ecosystem services in a number of ways. The health of soil is dependent upon complex bio-physical and bio-chemical processes which interact in space and time, and if they are managed effectively, they can make efficient use of nutrient resources and water for agricultural production. In doing so, loss of nutrients to surrounding land or water bodies or in wind erosion can be minimised. The availability of sources of phosphorus and potassium remain a significant issue for organic farms because of the requirement to use poorly soluble sources of these essential nutrients. Recent advances in microbial metagenomics and 3-D visualisation of the finest components of organic matter should lead to advances in understanding of processes that underpin transformations that support organic management. The interdependence of many soil physical and chemical processes that contribute to soil health is strongly linked to

activities of organisms that live in soil as well as to root structure and function. An integrated approach is required to capitalize on these contributions to soil health and associated ecosystem services.

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