Chapter 1

What is Soil Biological Fertility?

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1. INTRODUCTION

There is increasing interest in soil management practices that enhance biological contributions to soil fertility due to greater awareness of the need for sustainable farming systems (e.g. Lynam and Herdt 1989, Dick 1992, Roper and Gupta 1995, Doran *et al.* 1996, Swift 1997, Condron *et al.* 2000, Mäder *et al.* 2002, von Lützow *et al.* 2002). This has occurred due to the requirement for better fertiliser use efficiency which is essential in: i) developing nations where cost and availability constrain production (Swift 1997) and ii) many developed nations where public concern over environmental pollution from agricultural sources and associated government legislation restricts gaseous losses and nutrient leaching (e.g. N: Hatch *et al.* 2002, P: Leinweber *et al.* 2002). There has been a considerable decline in soil organic matter levels and associated loss of soil structure in many intensively cropped soils throughout the world. This has caused scientists

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and landowners to consider more carefully how various components of the farming system can be managed to more efficiently benefit from biological processes that improve soil fertility.

Soil biological processes are extremely diverse and complex (Lavelle and Spain 2001). Physical and chemical soil characteristics, climate, plant communities and agricultural practices influence soil biology in a magnitude of ways, with both positive and negative influences on the overall fertility of soil. This level of complexity constrains our ability to assess or predict the biological state of soil through measures of abundance of organisms or their activity (Pankhurst *et al.* 1997). The current inability to predict the outcome of a change in agricultural management on soil biological processes, with a subsequent understanding of what this means in terms of production or the environment, is a major constraint to the successful design of farming systems that harness the biological potential of soil. Many studies have attempted to define the biological status of soil using simple indicator measurements (Doran and Parkin 1994, Gregorich *et al.* 1994, Franzluebbers *et al.* 1995, Pankhurst *et al.* 1995, Walker and Reuter 1996, Stenberg 1999). Whilst this is appealing to scientists, land holders and policy makers, it is extremely difficult to find correlations between potential indicators and crop production, long-term sustainability and environmental impact. Part of this difficulty has been with understanding how organisms and the functions that they perform interact with chemical and physical soil attributes in agricultural soils to regulate crop production and influence the longer-term status of the soil resource. Due to spatial and temporal heterogeneity and the enormous diversity displayed in soil biological characteristics, it is not easy to use them to define 'best practice' for land management.

The focus of this book is thus to provide an overview of a range of biological processes that contribute to soil fertility and to discuss the manner in which management practices influence soil biological fertility. With the complexity of these biological processes in mind, the impact of major management options and farming systems on soil biological processes can be addressed. The consequence of this is the basis for sustainable use of the whole soil resource, which demands equal consideration of biological, physical and chemical contributions to soil fertility. Inclusion of information about soil biological fertility in farm management decision-making should allow more precision in selecting inputs that complement the capacity of a soil to sustain production and minimise environmental damage such as might be caused by nutrient loss. If the type of production at a site is changed, different biological, physical and chemical states might be required to sustain the soil resource there, depending on the production system in place. A set of biological characteristics necessary for sustaining the soil resource at a particular site cannot be prescribed because different farming systems, or even different stages in the same farming system, might require differences in soil biological fertility. Therefore, a suite of soil biological characteristics needs to be defined for each land use category according to the soil type and climatic conditions.

2. WHAT IS SOIL BIOLOGICAL FERTILITY?

There has been a great deal of discussion about the use of terms to describe the state of soil - e.g. soil quality, soil fertility, and soil health - as a means of improving recognition of the importance of the soil resource. In an agricultural context, the historical term - soil fertility - has the ability to convey all of the qualities required for plant and animal production. Soil has usually been investigated primarily from the perspective of pedological, physical, chemical and hydrological characteristics. This is the case even though soil organisms mediate a number of important pedological, physical and chemical processes (Lavelle and Spain 2001). The concept of soil fertility has generally been most concerned with soil chemical fertility and its ability to meet the nutritional needs of plants. For chemically-based farming systems, fertiliser requirements can be determined according to plant, soil and climatic conditions and extensive research has been carried out to identify these requirements in many agricultural situations. The physical constrains to soil fertility are also widely acknowledged and considerable effort has been expended in identifying land use practices that prevent or minimise development of structural constraints to plant growth or to soil loss through wind or water erosion. In contrast, much less is known about i) how to maximise benefits from soil biological processes (with the exception of symbiotic N fixation and biological control of plant disease), and ii) whether it is economically or environmentally sustainable to capture benefits from other soil biological processes.

The term ‘soil fertility’ used without the qualifiers ‘biological’, ‘physical’ or ‘chemical’ gives insufficient information about the state of soil. These three prefixes allow interpretation to be focused on components, or combinations of components, of soil fertility that are influenced by management decisions. Soil biological fertility has been used in this book in preference to terms such as 'soil biological quality' and 'soil biological health' within the framework set out in Table 1. Unfortunately, there are no simple, widely applicable and quantitative measures of any of the aspects of soil biological fertility because they are constrained by parent rock, soil origin, landscape and climatic factors as well as by land use. In spite of this, we recommended that the term *soil biological fertility* become widely used with reference to agricultural production systems. Without a focus on this component of soil fertility, the contributions of beneficial soil biological processes will continue to be consumed within the context of physical and chemical fertility and not recognised as an equally important aspect of the soil resource.

Table 1 Suggested working 'definitions' of soil fertility and its components: soil biological fertility, soil chemical fertility and soil physical fertility. The terms only have general conceptual significance because they cannot be quantified exactly or defined in specific units. For a particular site, the 'degree' of soil fertility (and components of soil fertility) depends on the inherent characteristics of the soil according to its origin and on the land management practices implemented.

COMPONENT OF SOIL FERTILITY	**'DEFINITION'**
SOIL FERTILITY	The capacity of soil to provide physical, chemical and biological requirements for growth of plants for productivity, reproduction and quality (considered in terms of human and animal wellbeing for plants used as either food or fodder) relevant to plant type, soil type, land use and climatic conditions.
SOIL BIOLOGICAL FERTILITY	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.
SOIL CHEMICAL FERTILITY	The capacity of soil to provide a suitable chemical and nutritional environment for plants and foraging animals for productivity, reproduction and quality (considered in terms of human and animal wellbeing) in a way that supports beneficial soil physical and biological processes, including those involved in nutrient cycling.
SOIL PHYSICAL FERTILITY	The capacity of soil to provide physical conditions that support plant productivity, reproduction and quality (considered in terms of human and animal wellbeing) without leading to loss of soil structure or erosion and supporting soil biological and chemical processes.

3. IMPORTANCE OF SOIL BIOLOGICAL FERTILITY TO AGRICULTURAL PRODUCTION

If the fertility of soil is considered in terms of short-term agricultural production alone, there may be little need for attention to soil biological processes in many developed nations where soils are inherently well supplied with major nutrients (for global soil nutrient maps see Figure 3, Huston 1993). This is because many of the benefits provided by soil organisms can be overridden by the indigenous nutrient supply or by the addition of synthetic fertilisers where inorganic nutrients and chemicals are readily available and relatively inexpensive. Biological processes that are exceptions to this are plant disease and symbiotic nitrogen fixation, which can both have significant effects on production in predominantly chemical-based agricultural systems. Generally, the emphasis of 'modern' agriculture, with widespread introduction of synthetic fertilisers, has largely ignored the potentially beneficial contributions of some soil organisms. This approach has lead to serious contamination of some environments by pesticides and nutrients including nitrogen, phosphorus or even trace elements such as copper. Furthermore, modern plant varieties have often been selected under conditions that are not favourable for certain biological processes (such as the function of arbuscular mycorrhizas (Smith *et al.* 1993)). This might create agricultural environments that cause some potentially positive aspects of soil biological fertility to be detrimental (Ryan and Graham 2002).

A pedological context to soil biology has been presented in great detail by Lavelle and Spain (2001). It provides a necessary perspective for evaluation of the importance of soil biological processes and for identifying underlying principles that can be applied across soil types and environments. It cannot be assumed that soil biological processes are effective unless demonstrated to be so for specific environmental and soil conditions. Furthermore, land management practices (such as fertiliser use) can alter soil conditions substantially to facilitate growth of agricultural plants that are not naturally suited to the original soil conditions. Other changes in both physical and chemical conditions might be able to be mediated by soil organisms if they are provided with an energy source (e.g. from manure, mulching or stubble retention).

Although larger organisms such as earthworms and termites can substantially influence the structural characteristics of soil, the greatest impact of smaller organisms is likely to be on soil chemical characteristics. Some chemical and physical processes in soil have significant influences on one another independently of biological processes. Thus, the interdependent nature and complexity of soil processes means that a simplistic view to its assessment is not appropriate.

It is not routine practice to prescribe soil biological conditions suited to the needs of individual farming systems at specified locations, although this is attempted with organic farming practices (Stockdale *et al.* 2001). Different sets of soil biological attributes may be more or less appropriate as farming practices are changed. If a soil has a high content of nitrogen or phosphorus (in terms of the adequacy of these nutrients for plant growth) it would probably be considered to be 'fertile'. However, this level of chemical fertility could have been derived primarily from synthetic fertiliser inputs. Alternatively, substantial contributions may have come from processes involving interactions between organisms, decomposition of organic matter and cycling of nutrients, or from a combination of organic and inorganic inputs and biological processes related to organic matter degradation. If soil organisms were major contributors to the high level of chemical fertility (through their interactions with organic matter inputs), corresponding positive contributions to the physical state of soil would most likely result. Furthermore, the biological processes and chemical inputs that contribute to soil chemical fertility can be linked. For example, higher fertiliser input leads to increased plant biomass that can enhance nutrient cycling through soil organisms if the organic matter has the required elemental content and is managed appropriately. The capacity of the soil to retain these nutrients is of great importance to their efficient use for agricultural production and to ensure that there is no loss into the environment through leaching and other means of dispersion.

From the perspective of enhancing and/or preserving the soil resource, the effect on the soil of increases in chemical fertility arising from either a biological or a chemical source may be quite different. However, evaluation of the biological component of soil fertility has generally been considered unnecessary when 'available' nutrient levels are 'adequate'. The evaluation of components of soil biological fertility presented in this book combine to demonstrate the breadth of contributions that soil biological processes make to the state of soil (Table 2).

4. MEASUREMENT OF SOIL BIOLOGICAL FERTILITY

There are well-established criteria for defining 'ideal' conditions of both soil chemical and physical fertility across diverse soils of different origins and in different climatic zones (e.g. Karlen and Stott 1994, Cass *et al.* 1996, Merry 1996). However, there is a lack of fundamental understanding of how soil biological, chemical and physical soil attributes interact and how they

Table 2 Examples of how management options influence soil biological processes and change soil fertility.

Management option	Soil biological processes influenced	Change to soil chemical fertility	Change to soil physical fertility
Organic matter Crop residue, farmyard and green manure incorporation, including composted household or green waste material.	Microbial populations enhanced. Initially may cause immobilisation of soil nutrients due to high C:N of organic residues. Soil faunal groups may increase or decrease depending on residue quantity and quality.	Increased availability of nutrients especially N, S and P. Cation exchange capacity increased (significant in low clay soils). Some potential for accumulation of heavy metals.	Improve soil structure through aggregation and water holding capacity.
Crop rotation Use of pastures including legumes.	Increased abundance of soil fauna, in particular earthworms.	C:N ratio decreased.	Preferential flow paths improving aeration and water infiltration.
Crop rotation Mixed plant species cropping.	Greater range of root exudates supports diverse microbial population.	Changes in C:N ratio.	Increased localised heterogeneity of soil.
Tillage Minimum/no tillage.	Encourages re-colonisation by soil faunal species and functional groups. Increase in overall faunal abundance and encourages greater diversity. Alters the bacterial:fungal ratio favouring fungal feeding faunal species. Concentrates soil microbial biomass into surface soil layer.	Decreased soil organic matter decomposition rates initially cause nutrient immobilisation. However, build up of soil organic matter results in greater net nutrient release.	Improved soil structure through aggregation and water holding capacity. Improved macro-pore formation.

Table 2 Continued on Page 8

Table 2 Continued

Management options	Soil biological processes influenced	Change to soil chemical fertility	Change to soil physical fertility
Controlled traffic	Minimises soil compaction resulting in higher soil faunal abundance and an increase in microbial biomass.	Increased availability of nutrients.	Improved total porosity leading to greater aeration and better water infiltration.
Livestock grazing	Provides a C-source, enhancing microbial and faunal activity, unless increased soil compaction decreases microbial activity.	Reduced mineralisation due to increased compaction and less organic matter.	Increased soil compaction.
Fertiliser High application rates	High P reduces mycorrhizal colonisation of roots. High N inhibits N_2 fixation. Nitrifier populations increased with NH_4^+ fertiliser. Some soil faunal groups increased.	Decreased availability of nutrients derived from soil biological processes. Soil acidification. Increased nitrate leaching to groundwater.	
Inoculants *Rhizobium* inoculation	N_2 fixation from the atmosphere. Introduction of more effective strains dependent on indigenous populations.	Increased N availability in soil on subsequent decomposition of legumes. Soil acidification.	
Inoculants *Penicillum radicardium*	Mineralisation of non-soluble P rich fertiliser products.	Increase P available to plant.	
Pesticides	Some beneficial soil fauna also killed. Potential to loose beneficial species completely, thus altering food webs.	Nutrient supply altered depending on shift in food web.	

are changed by agronomic management practices. Biological processes often have an indirect effect on plant growth (e.g. via nutrient availability or soil structure) making it difficult to illustrate a benefit to crop production. More than one combination of soil biological properties could be considered ideal, so it is difficult to define an optimal biological state of soil or the precise importance of biodiversity of organisms in agricultural soils.

Development of more quantitative research techniques to estimate biodiversity of organisms in soil and the dynamics of nutrient pools mediated by organisms have enabled specific management practices and more complex farming systems to be studied in ways not previously possible. For example, the development of techniques for assessing nutrients in the soil microbial biomass was a major advance for the rapid and routine study of soil biological processes associated with organic matter (Jenkinson and Powlson 1976-a, 1976-b, Brookes *et al.* 1982, Brookes *et al.* 1985). The capacity to quantify the mass of the bacterial and fungal population (compared to direct microscopy and plating techniques) played an important role in advancing knowledge of the dynamics of organic matter breakdown (Powlson and Brookes 1987) and associated nutrient cycling (Jenkinson and Parry 1989). In recent years, there has been a major advance in the assessment of more specific biochemical, functional and molecular characteristics of soil biology (Torsvik *et al.* 1990-a, 1990-b, Turco *et al.* 1994, Zak *et al.* 1994, Degens and Harris 1997, Tiedje *et al.* 2001, Murphy *et al.* 2003). These advances have allowed focus to shift from determination of types of organisms present to an assessment of the contribution of biological processes to key beneficial soil functions. The focus on identifying functional diversity of soil communities (Lupwayi *et al.* 1998, Kennedy 1999, Altieri 1999) provides the opportunity to determine causal effects on plant production and longer-term predictions of the future soil status.

In parallel with improved technology for assessing components of communities of soil organisms, emphasis has been placed on the importance of sampling strategies including time of sampling, depth of sampling, spatial distribution, storage of samples and use of volumetric units of measurement (Doran *et al.* 1996, Glendining and Poulton 1996, Sparling 1997, Degens and Vojvodi-Vukovi 1999, Shi *et al.* 2002, Smith *et al.* 2002). Although many technical advances have been made and new methods have become available for the assessment of specific components of soil biological fertility, it is essential to ensure that they are suitable to the soil conditions where they are used (e.g. Murphy *et al.* 2003). Inappropriate use of this technology, such as use without regard for local soil conditions, will lead to confusion and misinformation about soil biological fertility in relation to farming systems. The interpretation of data related to soil biological fertility remains an impediment to the development and implementation of models of nutrient cycling.

5. APPLYING KNOWLEDGE OF SOIL BIOLOGICAL FERTILITY TO FARMING PRACTICES

The complex nature of biological processes in soil is well recognised and it is not possible to characterise in detail the whole of the soil biology at every site. This means that day-to-day recommendations for improving the sustainability of farming systems are very seldom based on well-defined (if any) measures of soil biological fertility. Soil biological fertility is dynamic and quantitative measures vary greatly with time, even within short periods. The heterogeneity of soil biological processes in soil (Strong *et al.* 1998) presents further difficulty for quantification of soil biological fertility. Yet another problem is the conflicting views of what constitutes an ideal value. Crop production, long-term soil sustainability and environmental concerns often require opposing classifications of what is an acceptable indicator value (Sojka and Upchurch 1999). Therefore, the concept of defining acceptable and critical values for soil biological indicators has not been successful (Sojka *et al.* 2003). Thus 'one-off' measurements are not particularly useful for characterising the biological status of a soil. This contrasts with measures of other soil characteristics, such as pH, which change relatively slowly over time and allow 'one-off' measures to be applicable beyond the time of sampling.

Measurements of specific aspects of soil biology can be successfully applied to the comparison of management practices (e.g. tillage versus no tillage) or contrasting farming systems (e.g. organic versus conventional). Although measurements of soil biological characteristics are often difficult to interpret, their advantage over chemical and physical characteristics is that they are often more responsive to changes in management practice (Figure 1). For example, microbial biomass and biologically active fractions of soil organic matter turnover within months to a few years (Jenkinson and Ladd 1981) whilst the majority of soil organic matter takes decades or longer to turnover (Stout *et al.* 1981). Although it is generally not possible to define an optimal value for microbial biomass in a soil, if the microbial biomass or ratio of microbial biomass-carbon to total-carbon increased, this would be perceived as an improvement to the soil (Sparling 1997) even though it may not be expressed in terms of nutrient availability, plant production or yield (Fauci and Dick 1994, Sorn-srivichai *et al.* 1988). For this reason, such measurements are often well suited to monitoring programs where the emphasis is on assessment of the change in direction of a soil characteristic over time. Soil biological characteristics that change rapidly could be useful indicators of the impacts of agricultural practices. The current fundamental understanding of the importance of these characteristics to soil conditions can be used to make valued judgements as to the importance of the degree and direction of change of the indicators in response to agricultural practice.

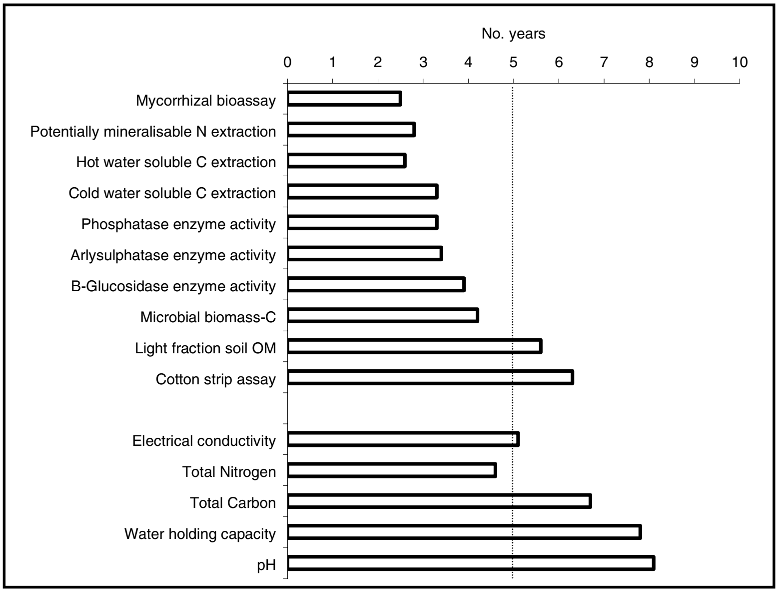

Figure 1 Number of years required to detect significant differences in soil measurements between management practices assessed on a grey clay soil (Sodosol) in south-western Australia (Milton et al. 2002). Land managers have a low uptake rate for soil monitoring (Lobry de Bruyn and Abbey 2003) and factors that take more than five years before a change can be detected are likely to have little impact on their decision-making.

Although soil biological characteristics can be monitored, this does not overcome the difficulty of knowing if they are either within an acceptable range or over an acceptable threshold value if one does indeed exist. Furthermore, the rate of change of the measured soil parameter may provide more insight into the impact of management on soil biological fertility than the magnitude of the parameter *per se*. Fundamental understanding of how specific soil biological characteristics respond to management practices is required if the characteristics are to be used as indicators. More importantly, information is required about the relationship between the biological characteristics and plant production, development of a sustainable soil matrix and/or prevention of environmental problems.

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