On farm

Soil Biology in Pasture Systems

Knowledge and Opportunity Audit

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Feedbase & Pastures

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1 LIST OF MAJOR RECOMMENDATIONS & "APPROACH TO RESEARCH"

(Priority in bold, marked*)

A. Setting the scene: diagnosis of problems (from section 4.1)

A1*. Diagnose pasture productivity constraints using **Water Use Efficiency** measurements to compare actual pasture productivity to **potential productivity**, and determine the nature of the constraints (both for research and on-farm).

NOTE: This work will set the target for pasture productivity and enable quantification of opportunities to improve current levels of pasture production.
Where current productivity is below potential and where the nature of the constraints is not known, ascertain whether the primary limitations are physical, chemical or biological. If there are major biological constraints, specific causes and treatments should be investigated.

Methods: fumigation and deep ripping trials, corrected for nutrition; measuring water use through soil profile.

A2*. Determine the likely positive contribution of changing management of the system (e.g. increased carbon and other inputs) in achieving potential pasture production, via improved soil biological functions such as nutrient cycling, nutrient use efficiency and disease suppression.

NOTE: This work may require several growing seasons, but will provide results that **cannot** be obtained via research towards **Recommendation A1**. In contrast to the identification of major constraints, which can often be done in one growing season.

B. Driving soil biological activity (from section 4.1.3)

Carbon inputs & availability

B1*. Soil carbon availability drives or constrains soil biological function in Australian soils. Determine the temporal dynamics of **carbon availability** (seasonal, field-based, comparing management regimes, within pasture & pasture/crop systems) and link this to key soil biological functions. Depending on agro-ecological zone (e.g. mallee cf western slopes) the key biological functions will differ (nutrient mineralization and loss, pathogen survival, pesticide degradation, soil aggregate formation). Management regimes include grazing systems, pasture composition, pasture renovation and soil ameliorants.

B2. Determine the role of grazing management in carbon dynamics, in relation to soils as carbon sinks and global greenhouse gas budgets. (Research in the USA, for example, is far ahead of Australia, and we cannot "import" these results).

Water availability & temperature:

B3. For key soil microbial processes (e.g. mineralization of N or development of disease suppression), define the number of microbially-optimal days based on conditions (soil type, soil moisture & temperature, based on weather data) found in different agro-ecological zones.

Aim: to provide information for prediction of soil biological function (**Link to A**).

C. Grazing management (from section 4.2)

C1*. Plant re-growth can be used as an indicator for resumption of grazing. Test the link between plant re-growth and key soil and rhizosphere biological processes. Does this method of scheduling grazing also deliver greater benefits from soil biological activity? (i.e. long-term sustainability of soil biological processes such as nutrient cycling). (Applied research).

C2.* *Appropriate grazing pressure could stimulate pasture re-growth via rhizosphere biological processes*.

Investigate rhizosphere processes over a range of grazing pressures that may lead to positive feedback on microbial mineralization of nutrients and their availability to plants (resulting in more rapid pasture re-growth). (Basic research).

C3*. Different grazing systems and grazing pressures lead to differences in soil biological functions (e.g. proportion of beneficial to deleterious organisms, nutrient cycling, disease expression or disease suppression). Determine the links between the composition and activity of soil biota under different grazing systems (linking soil biodiversity to function). (Basic research).

C4.* Determine the impacts of grazing management on soil food web dynamics, importance of various trophic groups in different agro-ecological zones and links to biological functions (dryland, lower rainfall). For example, food web dynamics in relation to synchronization of nutrient mineralization with plant demands. When plant demand is low, nutrients can be lost. If demand and supply of nitrogen do not match, excess accumulation of N could contribute to soil acidity problems.

C5*. *Minimize nutrient losses from grazing systems, especially in higher rainfall areas.* (Inappropriate grazing pressure could result in nutrient loss from the system via denitrification and by leaching).
Determine the role of grazing pressure in soil nutrient loss (especially N, but also P in high rainfall areas). Determine regulators of biological nutrient mineralization and loss, as affected by pasture composition: how can soil biota activity minimise the loss of nutrients from pasture soils? **Aim**: recommend grazing management to improve efficiency of resource use & reduce off-site impacts.

C6. Investigate the relationship between carbon inputs (seasonal, above- and below-ground) and biological processes associated with soil nutrient cycling within a field-based grazing system. **Aim**: to determine the balance between input of nutrients versus nutrients provided by soil biological activity, to gain more benefit e.g. mineralized nitrogen, also P availability in calcareous soils.

D. Management of pasture – crop transitions (from section 4.1.2)

Management of the transition from crop to pasture:

D1*. Seedling establishment and growth are important in the establishment of pasture and are affected by, for example, pathogen and nutrient status of soils. Develop measures of the status of key soil biotic activities in the transition from crop to pasture, to determine the impact of cropping phase management (e.g. nutrient cycling and availability, disease suppression). This is to provide information for farmers to maximize benefits from improved pasture soil biology.

Management of the transition from pasture to crop:

D2. Develop methods to evaluate a pasture soil prior to the next crop. Pastures provide a biologically-based benefit for the next cropping phase. For example, knowledge on disease potential, disease suppression potential, nutrient supply potential and soil aggregate stability at the end of a pasture phase will assist in deciding management practices for the next crop.

E. Soil-Borne Pasture Diseases: their Diagnosis and Control (from section 4.3.4)

E1*. Determine the major soil-borne plant pathogens for non-legume pasture plants (mainly grasses, including perennial and native grasses; region-specific; following from diagnosis of biological constraints). (Link to **A1**, determining constraints for pasture production).

E2*. Develop and deploy disease control measures, including chemical and biological treatments, for major soil-borne pathogens. Field-testing and assessment of potential for commercial development of bio-agents that induce systemic resistance to disease in pasture legumes.

E3*. Develop diagnostic DNA probes for the most important pathogens (fungi, nematodes; new research tools and methods for on-farm management of diseases). To be useful, this must be linked to information on the effects of environmental factors on disease expression.

E4*. Investigate the potential for development of disease suppression by promoting native microbial communities in pasture soils (i.e. control of disease by soil biological and/or physical factors while pathogen is present).

F. Removing negative impacts: Pesticides and pollution (from sections 4.1.5, 4.3.2, 4.3.3)

F1*. Establish the capacity of soil macrofauna such as dung beetle species to reduce pollution of water by pathogens and organic material (carbon and nutrients) that move from pastures into water catchments. (Determine compatibility with agro-chemical use).

F2. Determine the effect of agrochemicals on specific biota e.g. effect of anthelminthics on soil macrofauna, aiming to minimise collateral mortality.

F3. Determine the effect of new generation herbicides on plant disease expression and nitrogen fixation.

G. New Management options: System inputs and Pasture renovation (from sections 4.1.4 and 4.1.1)

G1*. Determine the full beneficial effect of pasture fertilizer inputs on soil biological activity (extent and duration of change in biological function), both directly and via improved plant growth. Consider this research alongside determining the benefits of greater carbon inputs.

G2. Pasture renovation to overcome soil compaction problems: compare the effect, benefit and cost of two contrasting approaches, i.e. soil physical disturbance versus changed grazing management, in different regions, for their ability to improve pasture soils and pasture productivity, especially via macrofauna activity.

<u>NOTE</u>: In addition to established methods in soil biology, the application of new tools to investigate soil biota and their activities will be valuable for progress. The use of these tools, based on advances in molecular biology and biochemistry, should aim to contribute to the research goals and priorities suggested in this report.

Approach to soil biology research in pasture systems

Soil biology research is often organism-based and less focused on the community interactions and the dynamics of soil biota populations. The organism-based approach to soil biology research has provided knowledge about soil biological diversity and role of specific soil biota in particular soil processes. However, biological functions at the plant production level under field conditions are mediated by diverse types of organisms and interactions between various levels of the soil food web.

Since the plant is the major source of available carbon for biological activity, especially in low fertility Australian soils, research on soil biota should consider the quality and quantity of carbon inputs from plants (through exudation and above- & below ground plant residues) and plant-induced changes in soil physical and chemical properties. Also, unlike cropping systems, pastures are composed of mixtures of plant types (legumes, grasses, C3, C4). The availability of carbon in pasture systems is mediated strongly by grazing management through above-and below-ground plant growth in response to grazing. Therefore, the development of options to manage soil biota should consider pasture composition and carbon inputs mediated through grazing management, in addition to soil organic matter.

Where and when are the resources and conditions favourable for soil biological activity? Soil physical and chemical conditions regulate soil biological processes and the distribution of biota in soil is heterogeneous, i.e. concentrated at few microsites. Even though the influence of soil moisture and temperature on biological processes is known, reliable estimations of biological functions in pastures in the field have been difficult to achieve due to the variation of the soil environment in space and time. In the majority of dry land cropping regions in southern Australia, moisture availability plays a critical role in determining the activity of both microflora and soil fauna. Temporal patchiness in favourable soil and environmental conditions, determine the actual contribution of plant-specific biological functions for crop productivity and soil health. Such information would allow more accurate estimates of the likely contribution of soil biological activity to pasture production and environmental health in field situations. Soil structural aspects such as habitable pore space and the physical distribution of microsites rich in biota) and variation in moisture and temperature (hence also oxygen) need to be considered in placing soil biological research into the field context.

By considering the interactions between the three main components of a pasture system, i.e. plant production (plant type and grazing management), environment (soil and climatic) and soil biota (populations of functional groups and activity), research should provide information on how the regulating factors affect biota dynamics and activity in a field context (Appendix 8). This approach to research should in turn lead to development of management options related to grazing, rotations, system inputs to best utilize beneficial soil biological activity and minimize losses, e.g. due to disease and negative environmental impacts.

Pasture production is supported and enhanced by soil biological processes. There are likely to be substantial opportunities to increase pasture production towards the potential production target based on water use efficiency. Research on soil biology in pastures should focus on removing constraints to production and increasing input (water and nutrient) use efficiency. Using this approach, yields in cropping systems have increased substantially towards the potential, based on water use, over a period of 20 years. Research on biological components and interactions in a farming systems context, using potential plant production as a benchmark, has the potential to substantially improve pasture production and sustainability.

2 INTRODUCTION: SOIL MICROBES IN PASTURE SYSTEMS

Soil is one of our most precious non-renewable resources and the soil biota represents a large portion of the earth's biodiversity. Soil organisms regulate a majority of ecosystem processes in soil that are essential for plant growth (nutrient availability and disease incidence), soil health (soil structure and agrochemical degradation) and sustained productivity (development and maintenance of physico-chemical properties of soil). Soil organisms can be grouped according to their size (e.g. microflora, microfauna, mesofauna and macrofauna), phenotypic (morphological) characteristics (e.g. *Bacillus* sp. vs. *Rhizobium* sp.), function (e.g. nitrifying micro-organisms) and trophic preference (e.g. bacterial or fungal feeding nematodes).

In a low input farming system, a large, diverse and active soil biota helps to provide soil conditions for sustainable pasture production through (a) improvement of nutrient supplying potential of soils and input use efficiency (e.g. nitrogen fixation and nitrogen mineralization, P uptake, water use), (b) preventing aggressive plant pathogens taking hold, (c) improving plants' ability to withstand disease and (d) stabilizing soil structure thereby reducing the loss of nutrient-rich top soil. In high input farming systems, it is essential to maintain adequate activities of key microbial groups (functions) to maximize input use efficiency (e.g. fertilizer), to reduce off-site negative environmental effects (loss of nutrients, movement of dissolved organic carbon and pesticides, soil acidity) and reduce disease incidence.

Major constraints for biological activity in Australian environments are lack of carbon and available nutrients, and relatively short periods of optimum moisture conditions, which can vary significantly with respect to season and plant growth cycles. The concept of microbially optimum days (based on moisture and temperature) has been developed for cropping systems. The aim was to determine the overall function for specific soil biological processes under field situations in different agro-ecological zones. Such information for pastures would help to predict the potential of biological function to contribute to pasture production (e.g.

estimates of amount of N mineralization would impact on rates of fertilizer N application; estimates of disease suppression would help decide crops in rotation).

The various soil and environmental factors that regulate biological activity differ for different functional and trophic groups of biota. In the majority of agricultural soils in Australia, most biota are concentrated in a thin layer of surface soil (>50% in the top 5 cm) which is prone to environmental extremes (lack of moisture and high temperatures) and erosion loss. In addition, the distribution of biological activity in soils is patchy, concentrated in 'hot spots' such as decomposing crop residues, animal excreta and the rhizosphere.

Soil-Plant-Biota interactions are influenced by the size relationships of the participants as the soil habitat is composed of differently sized pores, interconnected by necks of varying sizes and biota groups of different size classes. Surface soils in general are heterogeneous and the soil matrix is patchy in terms of substrates, environment and protective niches for different groups of biota. Thus in assigning the functional significance of soil organisms we need to recognize the microsites / hot spots / spheres of influence of biota in order to (a) determine the regulators of various biological functions and (b) be able to manipulate the biological functions for sustainable agricultural productivity and maintain soil resource quality.

The importance of these centres of influence (microsites) is great in Australian soils, which are carbon- and fertility-poor. In Australian soils the two microsites that contribute to the majority of biological activity (by harbouring populations and support activity) are: (a) the rhizosphere - soil surrounding roots and (b) the soil near decomposing crop and animal residues. The other centres of activity are associated with micro- and macro-aggregates and with biopores (pores created by the activity of large fauna such as earthworms, ants, beetles etc or previous crop roots). The contribution of soil aggregates to total microbial activity in Australian pasture soils, especially pasture-crop rotations, is lower than in other countries because of lower carbon levels and differences in soil chemical properties. The importance of biopore-associated biological activity has been recognized recently and may play a significant role in the overall biological fertility of pasture soils in specific situations e.g. root zone-constrained soils. The importance of biopores, created by macrofauna, in soil structure development and extension of biological activity to deeper soil layers could contribute to a large extent to the overall biological functions in continuous pastures. In pastures with large populations of macrofauna such as earthworms, their casts could form new centers of biological activity with significant contributions to the overall soil biological activity.

The biopores associated with organic matter burial by macrofauna (e.g. dung by dung beetles and litter by earthworms) may provide a rich haven for microbial activity in the moist deeper layers unlike the dry and hot conditions that exist in surface layers. Crop residues from the cropping phase (especially under no-tillage systems), may form centres of biological activity, but because only fresh crop residues can provide easily available carbon substrates, the contribution of crop residues may be less than expected. In addition, unlike the rhizosphere, the availability of essential nutrients for microbial activity may not be adequate with crop residues.

Unlike annual crops which are normally grown as monocultures, pasture systems normally consist of several plant species and are much more variable, in morphology, space and time, than crops.

In perennial pasture systems, there are usually no single major disturbance events, and therefore carbon inputs from plant roots and litter are the major regulating factor for biological succession in these soils. In contrast, annual tillage of soil in cropping systems is a major disturbance that re-starts microbial successional cycles. In the crop-pasture system, this occurs at the end of the pasture phase.

Microbial succession occurs together with the ongoing food web cycle in the rhizosphere of growing pasture plants. In pastures, biota interactions in litter and soil occur at two major types of microsites: (a) growing and dead roots distributed through the soil and (b) the litter layer on the surface, with the amount present depending on grazing intensity. The soil physical and environmental factors to which these two types of micro-sites are exposed are quite different, and so they tend to support or promote different groups of soil biota (in both functional and trophic groups across the entire soil foodweb). The two types of micro-sites also differ in the quality of the carbon substrate available to the biota, e.g. substrates in the rhizosphere are more easily metabolizable (lower C/N ratio, less lignified material) than either the litter at the surface or dead roots (wider C/N ratio, more resistant material).

Microbial decomposition of the litter at the surface requires that it be incorporated into the soil through the action of macrofauna (earthworms, termites) or mechanical disturbance (tillage), which is similar to the microbial breakdown of crop stubble in reduced till cropping systems. Substrate decomposition and foodweb composition has been shown to be fungal dominated in reduced till cropping systems in many countries including Australia (Beare et al., 1992, 1995; Roper and Gupta, 1995). Decomposition of pasture root material (from dead roots and root shedding following grazing) and turnover of carbon from root exudation is more influenced by its location within the soil matrix, e.g. in macropores or encapsulated within soil particles, than the material at the soil surface. Therefore physical protection and accessibility of substrate to microbiota, both factors that are heavily influenced by soil physical conditions, play an important role in the composition and activity of various microbial and faunal groups within the soil.

In permanent pastures, especially in higher rainfall areas, soil biological activities, together with soil structural and physical conditions, play an important role in ecosystem functions both within the pasture and in the wider landscape. This is in addition to soil biological processes that are important for plant growth and productivity. The transport of nutrients, carbon and pollutants (herbicides, pesticides, animal/human pathogens) through the soil at the landscape scale depends on physical and biological soil properties. On a regional level, where the landscape is dominated by permanent pastures, the soil biological component will be more significant than it is in an annual cropping system (in particular the traditional tilled cropping systems) because of the lack of regular soil mechanical disturbance. An imbalance in nitrogen cycling processes, i.e. lack of synchronization between the production and requirement of mineral nitrogen resulting in excess N accumulation, has been suggested as one of the causes of soil acidity in pasture-based farming systems in eastern Australia.

The presence of large quantities of labile organic matter from litter and decomposing root material provides optimal conditions for the production of greenhouse gases (e.g. methane, nitrous oxides) through the activities of specific soil microbial communities such as methanotrophs and denitrifying organisms, particularly in high rainfall regions. Weier and MacRae (1992) observed that majority of denitrifying bacteria isolated from a permanent pasture on a brigalow clay were N_2O producers. As nitrate N is accumulated due to the inefficient use of available nitrogen, the presence of large quantities of labile C from litter fulfils two of the necessary criteria for denitrification with soil water content being the major regulating factor.

3 EFFICIENCY OF USE OF INPUTS (WATER, FERTILISER) & BENEFITS OF MANAGING SOIL BIOTA

Better management of soil biological activity can (a) improve resource use efficiency (i.e. save graziers money), (b) improve soil quality (through build-up of higher soil organic matter, better biological fertility and reduced disease) and (c) reduce environmental degradation both on-farm and in the wider environment (less soil erosion, reduced accumulation of contaminants and nutrient losses).

Results from 'Sustainable Grazing System' (SGS) trials show that many pastures in the different agro-ecological zones of southern Australia are not performing to their full potential (see Section 4.1) in terms of plant productivity per unit of input of water or nutrients.

The efficient use of soil resources and inputs for pasture growth requires (a) synchronization of nutrient availability to plant requirement, (b) lack of constraints (plant pathogens, chemical residues, hostile subsoils) for plant growth, and (c) ability of the plant to recover from previous grazing. Plant-biota interactions have an important role in (a) and (b) and these are in turn heavily influenced by grazing management (linked to c – the ability of a plant to recover depends on the intensity of grazing and is related to the seasonal conditions).

The importance of soil biological functions essential for plant growth and the magnitude of the effects have been clearly demonstrated both under controlled environmental conditions and in field experiments using various experimental techniques. These include (a) inoculation of specific biota species into sterile or non-sterile soils (inclusion experiments), (b) removal or reduction in populations of a particular species of biota (exclusion experiments) and (c) soil fumigation using chemicals such as methyl bromide. Soil sterilization by other methods such as gamma irradiation, autoclaving and steaming has been used in experiments under controlled environmental conditions. The effect of chemicals is generally not limited to single species or group of biota and non-target effects on other groups of biota are commonly observed. However these methods have provided opportunities to investigate the mechanisms of biological processes in particular the soil borne plant diseases. Some of the examples demonstrating the importance of biological activities for plant growth and productivity in grain crops include:

The role of pathogenic soil biota in decreasing grain production in wheat was clearly shown by David Roget (CSIRO Land and Water, unpublished) in a SA soil using crop rotation and soil fumigation experiments (Appendix 4a). Under low N status, soil fumigation, which was used to kill the fungus that causes take-all disease of wheat, significantly improved wheat yields by ~50% and crop rotations with managed legume pastures (i.e. with grasses removed to reduce the carry-over of pathogen inoculum and with benefits from N_2 fixation) further enhanced wheat yield.

A number of such examples demonstrating the benefits from removing biological constraints are available for cereal production but little or no such data is available for pasture production, especially under Australian conditions.

Evidence from overseas, i.e. New Zealand, USA and Zimbabwe, clearly indicates the beneficial effects of managing soil biota to the growth of pasture plants such as alfalfa, clover and grasses (Rodel and Shepherd, 1972; Yeates et al., 1975; Gupta and Willis, 1982). For example, Yeates et al. (1975) found in NZ soils that fumigation with methyl bromide, which reduced infestation by clover cyst nematode, increased dry matter yields by 46% during periods of nematode activity. Evidence to indicate significant benefits from managing soil biota in pasture production may exist as unpublished observations but published reports on the magnitude of biota contribution to pasture production in well planned field experiments under Australian environments are very rare.

van Vliet et al. (as reported by Gupta et al. 1998) conducted an experiment to determine the effect of increasing the complexity of the soil fauna community on the decomposition of lupin crop residues and plant uptake of available nutrients (nitrogen) in a WA soil (Appendix 4b). They found that shoot and root weights of wheat plants increased 54% and 72 %, respectively, when all groups of microflora, micro- and mesofauna were present compared to microflora alone or with fewer groups of fauna only.

Research on the mechanisms of soilborne disease suppression during the last 10 years has indicated that it is attributable both to the presence of specific microfloral communities and interactions between microflora, microfauna and mesofauna (Gupta and Neate, 1999; Barnett et al. 2001). Gupta et al. (1999) found that deliberate reduction in populations of one the components of the soil food web, i.e. mesofauna, resulted in greater disease incidence (*Rhizoctonia solani)* and reduced plant growth (Appendix 4c).

Roget (1995) reported the development of *R. solani* disease suppression under broad acre field conditions at Avon, South Australia (Appendix 4d) and this phenomenon is biologically regulated (Wiseman et al., 1996). The development of disease suppression at the Avon experimental site has been clearly demonstrated for the cereal phase of the rotations. Even though no detailed assessment of suppression development was made on the pasture phase, visual observations suggested that significant changes in disease dynamics were occurring. In the initial years of the trial, patches of poor growth (particularly in medic) due to the presence of *R .solani* were regularly observed. These patches of poor growth were estimated to account for up to 30% of the plot area. In later years, as the level of general suppressive activity increased, the poor growth patches were no longer evident (David Roget, CSIRO Land and Water, personal communication).

Soil-borne plant diseases caused by different types of biota (e.g. fungi, bacteria, nematodes etc) have generally been major constraints of crop productivity. Even though a variety of solutions have been developed to control or avoid crop losses from higher levels of plant diseases, critical obstacles still exist in our ability to minimize plant diseases and their impact on pasture productivity. In the past, much of the research on soil-borne pathogens has concentrated on host-pathogen interactions alone. Recent findings on soil borne plant diseases in grain crops clearly indicates that in addition to the epidemiological data of the pathogen, sound ecological understanding of host plant-pathogen-soil biota interaction is critical for the development of options to reduce plant disease impacts, including disease prediction capabilities.

For example, the development and widespread adoption of the model for prediction of take-all disease of wheat required both a thorough understanding of the pathogen, its epidemiology and ecology and the availability of a DNA based technique to measure pathogen levels in soils (Roget, 2001). This model not only estimates inoculum level, disease occurrence and crop yields but also economic outputs based on a range of environmental, management and financial options. Currently no such models are available for pasture disease management. In view of the recent developments in our understanding of soil biota interactions and the molecular techniques to identify and quantify plant pathogens, a huge potential exists for the development of such predictive tools that could be used in pasture management.

4 REVIEW RELEVANT INTERNATIONAL SOIL BIOLOGY LITERATURE (TO DEVELOP AN OVERVIEW OF THE CURRENT STATE OF PUBLISHED KNOWLEDGE ON SOIL BIOLOGY UNDER PASTURES)

The biological scope of this review includes the soil micro and meso-fauna and flora, beneficial and pathological organisms and plant roots.

We present a short list of important biological functions that affect pasture growth and productivity including root growth and function, both in permanent pasture and in pasture – crop rotations.

- Carbon mineralisation (overall microbial activity, as influenced by composition and activity of various groups of soil biota) which regulates disease (suppressive soils), nutrient availability, nutrient loss (leaching, denitrification), soil loss (structure and erosion) and decomposition of litter and roots.

- Nitrogen and Sulphur mineralisation and fixation (symbiotic and non-symbiotic N_2 Fixation), S cycling, related to pasture quality (and wool quality).

- Phosphorus availability and movement (P solubilization, uptake into plants, mycorrhizal fungi).

- Soil aggregate formation and soil structure (networks of fungal hyphae and pore size distribution, soil fauna activity; related to carbon content and carbon mineralisation).

- Disease and disease suppression: pathogens, microbial suppression of disease (reducing the pathogen population or decreasing disease incidence through competition or antagonism), biological controls.

- Herbicide, insecticide and fungicide degradation.

- Plant shoot growth promotion: to aid pasture establishment and pasture renovation by resowing (relative plant density and pasture composition).

- Plant root growth promotion: root length and volume, rate of root growth during seedling establishment, pasture renovation or regeneration, compensation for diseased roots.The place of soil biological activity in the functioning of a soil - pasture system and some key interactions between soil biota and other grazing system components are shown in Figure 1.

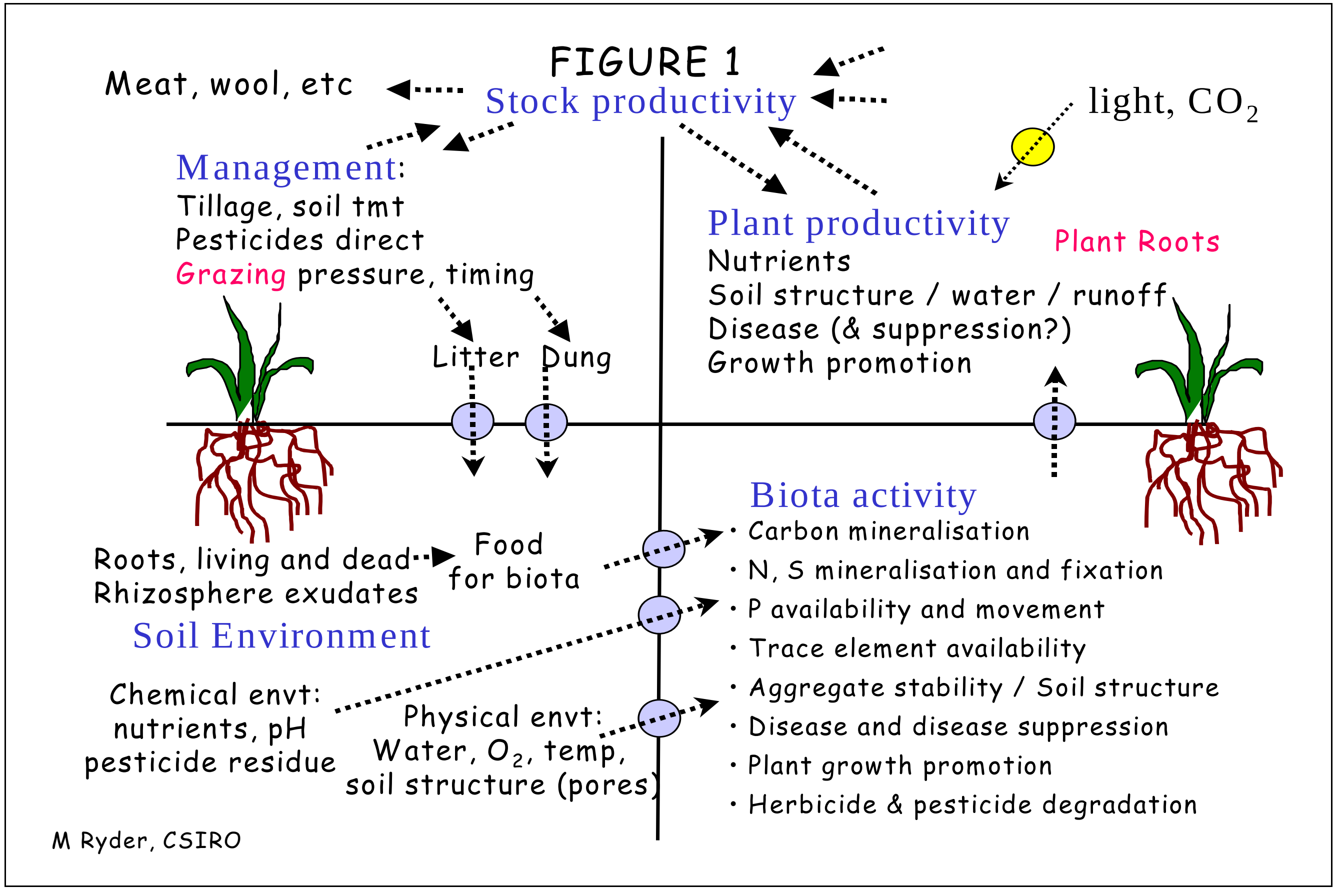

FIGURE 1
Meat, wool, etc
Stock productivity
light, CO_2
Management:
Tillage, soil tmt
Pesticides direct
Grazing pressure, timing
Plant productivity
Plant Roots
Nutrients
Soil structure / water / runoff
Disease (& suppression?)
Growth promotion
Litter
Dung
Biota activity
Carbon mineralisation
N, S mineralisation and fixation
P availability and movement
Trace element availability
Aggregate stability / Soil structure
Disease and disease suppression
Plant growth promotion
Herbicide & pesticide degradation
Roots, living and dead
Rhizosphere exudates
Food for biota
Soil Environment
Chemical envt: nutrients, pH pesticide residue
Physical envt: Water, O_2, temp, soil structure (pores)
M Ryder, CSIRO

4.1 Impacts of management on soil biota and soil biological properties: setting the scene

In contrast to fields that are cropped annually, management of pastures in southern Australia may involve a reduced number of on-field practices, and this is especially so in permanent or continuous pastures. The pasture phase in pasture-crop rotations is also influenced by the practices that were used during the previous cropping phase. For example, herbicides applied during a cropping phase can affect plant establishment during the pasture phase.

The various management practices that are involved in pasture and pasture/crop production have been shown to affect both the populations and the activities of different groups of beneficial and deleterious biota across all soil types and cropping regions. The impact of the different agronomic practices on soil biota is either directly on the organism populations or caused by changes in the soil habitat (e.g. physical and chemical properties), microclimate and carbon (energy) sources. Crop rotation, an integral part of most Australian cropping systems, influences soil biota directly through the effect of plant type and indirectly through the associated agronomic practices.

Some of the agronomic practices that are used in dryland pastures which can impact on populations of biota involved in nutrient availability and disease control include: (a) tillage, (b) type and intensity of grazing, (c) application of herbicides, (d) application of insecticides and fungicides, (e) application of manures or fertilizers and (f) application of chemical amendments or waste products. In addition, stubble management practices that are used in the cropping phase will also affect the biota in the pasture phase.

In general, the level of knowledge about soil biota and the processes they carry out is much better in cropping systems, and in the cropping phase of crop-pasture rotations, than in the pasture phase or in permanent pastures. In recent years, the productivity of cropping systems has been improved substantially through the application of research that has enabled farmers to overcome soil biological constraints and to benefit from the activities of soil biota. Much of this gain has been through changes in management rather than by simply changing inputs, although greater use of inputs may be necessary for maximal improvement. This same opportunity to improve productivity is likely to be achievable for pasture-based production systems.

A concept that has proved to be extremely useful to cropping systems and should be considered in pasture systems is potential yield based on growing-season rainfall (French and Schultz, 1984). A generally accepted water use efficiency (WUE) target for cereal crops in southern Australia is 20 kg grain yield / ha / mm water used by the plant for grain production. For dry matter production of cereals, this value is 55 kg dry matter / ha / mm water used by the plant (French and Schultz, 1984). Even though such estimates for pasture production are rare, a potential production target for a legume pasture is suggested to be 45 kg dry matter / ha / mm water transpired (i.e. used by the plant; French, 1991). According to the recent Sustainable Grazing Systems report, the WUE for three seasons across the region in southern Australia is below this target (ranging from 2-19 kg DM / ha / mm rainfall) and is most often around 50% of the target. Results from various pasture production trials suggest that poor plant establishment, incidence of diseases, inadequate nutrition for top growth and limitations caused by weeds are some of the key factors that could lead to this lower water use efficiency (French and Schultz, 1984; Bellotti, 1998a). We expect that in many situations farmers still do not know what their potential pasture production is, and according to recent data, production is likely to be well below potential. Although pastures are more complex than a crop in terms of plant composition, the use of WUE as a production yardstick would still enable targets to be set and improvements to be measured.

As suggested above, available information on the effects of management practices on soil biota and biological functions in pastures is patchy. Most of the research in dryland pasture systems has concentrated on the *Rhizobium* – legume symbiosis, certain diseases of pasture legumes and the population dynamics of earthworms. Very little information is available on the dynamics of other essential functional groups of biota and the dynamics of biological functions and their regulating factors.

Although a great deal of research has been done on grazing management, little connection has been made between grazing and soil biota, despite the fact that grazing is one of the primary determinants of food resources for soil biological activity. In addition, much of the information has tried to establish differences between pasture and crop systems and very little is known about the dynamics of biota within pasture systems nor is much known about the transition effects associated with changes between cropping and pasture phases. Such information is necessary for the development of management options to improve pasture production and to maintain soil resource quality in pastures. As there is limited information on the impact of various management practices on soil biota in Australian dryland pastures, we included research from NZ pasture systems in this discussion, even though soil and environmental conditions are substantially different between the two countries. In addition, research from other countries that has contributed to the understanding of biota dynamics in pastures is also included.

Recommendations:

Setting the scene: diagnosis of problems

1. Diagnose pasture productivity constraints using **Water Use Efficiency** measurements to compare actual pasture productivity to **potential productivity**, and determine the nature of the constraints (both for research and on-farm).

   NOTE: This work will set the target for pasture productivity and enable quantification of opportunities to improve current levels of pasture production.

   Where current productivity is below potential and where the nature of the constraints is not known, ascertain whether the primary limitations are physical, chemical or biological. If there are major biological constraints, specific causes and treatments should be investigated.

   Methods: fumigation and deep ripping trials, corrected for nutrition; measuring water use through the soil profile.

2. Determine the likely positive contribution of changing management of the system (eg increased carbon and other inputs) in achieving potential pasture production, via improved soil biological functions such as nutrient cycling, nutrient use efficiency and disease suppression.

   NOTE: This work may require several growing seasons, but will provide results that **cannot** be obtained via Recommendation 1. This is in contrast to the identification of major constraints, which can often be done in one growing season.

3. **Note** that we have treated **grazing management** as a separate part of this review – please refer to **Section 4.2**.

4.1.1 Soil disturbance: Cultivation / compaction / ripping

Information on the impact of soil compaction on functional groups of soil biota and biological functions is patchy. However, clear evidence exists for a reduction in microbial activity and that some groups of biota are negatively influenced by soil compaction in pasture systems. Such information is not available for pasture systems in large parts of southern Australia. Information is available on the effect of compaction on populations and types of macrofauna (e.g. earthworms). Management practices that loosen the soil to remove compaction (i.e. ripping and organic matter addition) have been shown to improve pasture plant growth. Both shoot and root growth were improved. Improvements in microbial activity have also been reported.

Information on the benefits of cultivation (ripping) or other practices to remove compaction effects i.e. addition of organic matter and/or soil ameliorants on biological functions or microbiota (both beneficial and pathogenic) is required.

Soil compaction, as a result of livestock treading and/or machinery use, causes increased bulk density, reduced macropore volume and overall structural degradation and has a significant effect on pasture productivity and in turn on the sustainability of livestock farming.

There has been considerable research that shows the problems arising from soil compaction and structural degradation of Australian pasture soils (Goss et al., 1984; Harrison et al., 1994; Burgess et al., 2000; Francis et al., 2001). Problems from soil compaction associated with naturally occurring layers of high bulk density i.e. clay pans and dense textural B-horizons have also been recognized (Harrison et al., 1994). Soil compaction and associated structural degradation (such as decreased macro-porosity, reduced movement of air and water etc) not only reduce root and shoot growth by impacting soil biota activity but also affects different trophic groups of soil biota. Burgess et al. (2000) wrote that non-aerated soils have a macroporosity of less than 10% and a penetration resistance of >2 Mpa and that this represents conditions of poor aeration and reduced movement of water and nutrients.

Reduced root growth, due to soil compaction, which in turn limits the carbon food source for soil biota is one of the major reasons for negative effects of compaction on biological activities. The availability of habitable pore space, i.e. pore size distribution within the right size range, suitable pore connectivity and the presence of the right ratio of soil water to air filled pore space, is critical for the soil biota to survive and grow, and therefore to impact positively on soil biological functions.

A large body of evidence is available on the effects of soil compaction on the populations of macrofauna, and earthworms in particular. For example, compaction of the wet soil surface of a black cracking clay (Vertisol) in Queensland reduced numbers of macrofauna (herbivores, predators, ants, spiders, earthworms and other detritivores) (Radford et al., 2001). Agricultural machinery used in cropping caused the compaction. The reduced numbers of macrofauna in compacted treatments were attributed to reduced ground cover (reduced food supply) and less favourable habitat (quick drying of soil and more extreme temperatures). However, information on the effects of compaction, and soil treatments to remove compaction, on the size and activity of essential functional groups of soil biota in southern Australian pastoral soils is limited and patchy.

Red brown earth soils which are distributed across large parts of southern and eastern Australia are known to be weakly structured and prone to degradation both due to the animal treading in permanent pastures and improper tillage practices in pasture-crop rotational systems. Structural deterioration in these soils includes loss of stable aggregation resulting in degradation of pore structure hence decreased water infiltration and increased runoff. This will lead to a decline in the quality of habitable pore space for soil biota. Reduced plant biomass (root and shoot) means that lower levels of carbon will be available for biota. The role of pasture plants such as ryegrass and soil biota i.e. fungal hyphal networks, in aggregate formation and stabilization has been well researched. A well developed pasture phase is necessary to gain benefits from plant-biota mediated processes in terms of water-stable aggregation and restoration of soil structure to a level adequate for sustainable farming (Gardner et al., 1992; Smettem et al., 1992).

Management practices such as deep ripping, shallow mechanical loosening, subsoil loosening etc. that are recommended for alleviation of problems caused by compaction have been shown to improve plant growth, both above ground and below ground in different soil types (Cortez & Hameed, 2001; Burgess et al., 2000; Gardner et al., 1992; Smettem et al., 1992). These management practices would increase biota populations by improving the availability of carbon food source and by improving the soil physical properties i.e. habitable pore space. Reduced bulk density from mechanical loosening of soils also removes physical constraints for the movement of macrofauna through the soil profile. Subsoil loosening to depths of 25-50 cm, has led to increased hydraulic conductivity and improved pore systems, permitting more rapid root growth (Harrison et al., 1994). These improvements in soil physical conditions below the normally microbially-rich surface soils have the potential to increase zones of microbial activity down the soil profile, along with the increased root biomass. Since these soil treatments also improve the habitat for movement of macrofauna, they have the potential to result in an overall improvement in biological functions, provided other constraints such as soil chemical limitations are not present.

Most of the information on the effects of deep ripping, shallow or subsoil loosening has concentrated on plant growth and soil physical conditions. Very little effort has been made to link changes due to these management practices to changes in soil biological functions. Burgess et al., (2000) reported that the timing of shallow mechanical loosening (or aeration) is critical for optimal soil and pasture responses, i.e. there was a narrow window in late spring when soil conditions, rainfall and evaporation were ideal for modification of pasture systems near Hamilton, New Zealand. Implementation of management practices during optimum seasonal conditions is also necessary to increase the length of time that the benefits are available to both soil and pasture plant productivity. Since soil biota and biological functions have a vital role in realizing the improvements in soil conditions and plant productivity following disturbance, it may be necessary to consider the biological status of soils when decisions are made about the nature and timing of mechanical disruption of compacted soil. Very little work has been done in this regard.

The release of protected organic matter after soil disturbance causes a short-term flush in microbial activity. However, such releases of protected organic matter for microbial decomposition may lead to reductions in soil organic matter levels if these events happen more quickly than the system is able to build up or add organic matter through plant biomass. It is well known that cultivation-induced reductions in soil organic matter are mainly a result of the microbial decomposition of biologically available carbon released after disturbance, i.e. removal of physical protection, increased contact between above ground litter and soil and release of easily available carbon compounds. Long-term or inappropriate cultivation results in a loss of soil structure, reduces infiltration capacity and increases runoff in some soils (Malinda, 1995; Gardner et al., 1992).

In pasture-crop rotations, it has been shown that the type of cultivation used to bring the pasture phase back into cropping could have a significant effect on the potential benefits from the pasture phase, e.g. organic matter accumulation, aggregate stabilization etc. Intensive cultivation during the crop phase could result in a loss of biologically-available carbon and cause dramatic changes in soil biota, so that recovery during the next pasture phase may take longer.

Any reductions in biota populations and biological functions during the cropping phase would lead to reduced benefits from biota for growth of plants in the next pasture phase, so that inputs may be required for the establishment of a productive pasture. The effect of tillage during the crop phase is also linked to options for stubble management (such as retention or burning) in relation to soil biota and biological functions. Most of the research in pasture-crop systems has concentrated on the crop phase, with little or no work on the effects of cropping phase, in particular tillage effects, on pasture productivity (Research in this area would potentially be collaborative research sponsored by both GRDC and MLA). In order to gain maximum benefits from the pasture phase, it may be necessary to implement appropriate management options, e.g. tillage and crop residue retention, during the cropping phase. Similarly, the development of techniques to manage pastures immediately before the cropping phase to optimize the contribution of soil biota to crop productivity is an important but under-researched aspect of transitions between crop and pasture phases.

Research on the effect of physical disturbance on the composition of soil biota (foodweb) and the activity of various trophic groups in the foodweb suggest that intensive tillage results in predominance of bacteria-feeding foodweb components compared to a dominance of fungal-feeding biota groups in undisturbed systems. Such information comes mainly from cropping systems only. Information on the effects of ripping and other types of mechanical disturbance in pastures is lacking with respect to changes in the functional groups of soil biota and the dynamics of biological functions. Evidence on soil macrofauna suggests that populations increase following removal of soil physical constraints.

Even though soils in pasture systems, especially continuous pastures, experience less physical disturbance, grazing causes disturbance that is mediated through large changes in carbon availability and this is likely to have a substantial effect on the temporal dynamics of soil biota and associated biological functions. Very little information is available on the effects of grazing system (type of grazing / timing of grazing) on biota composition, activity and ecosystem functions (additional discussion in Section 2).

One of the most promising areas of investigation is controlling the synchrony of plant nutrient requirement with microbially-mediated nutrient release in pasture-cropping systems, by managing the quality and position of litter in the soil physical environment (via tillage). Similar efforts to synchronize nutrient release to plant requirement in permanent pastures may be achievable through management of grazing (intensity / timing). Pasture species composition (via litter chemical quality and physiological growth properties, e.g. C3 / C4 metabolism, legume / non-legume, annual / perennial, rooting pattern) will contribute to microbial activity, C turnover and nutrient release patterns.

Microbially-mediated nutrient release is significantly affected by soil structure because it interacts with the physical placement of the litter (e.g. via tillage), natural physical causes (e.g. wet-dry conditions) and natural biological causes (e.g. activity of macrofauna, animal hooves, small mammal tunnels). The primary determinant of the timing of litter accumulation is the intensity and timing of grazing, but subsequent tillage events in pasture-crop rotations will also produce changes in placement of organic matter that may be of more importance than the initial placement of crop residue onto/into the soil. Soil structure, e.g. via bulk density and pore size distribution, can influence root growth pattern and hence can affect root exudation and associated microbial composition and activities.

The tilth of the soil ("the physical condition of the soil in relation to plant growth") interacts with (a) the timing of availability of crop residue to soil microbes and (b) natural environmental factors (e.g. temperature and rainfall) to determine the how much nutrient can be liberated from new crop residues and SOM from previous years inputs. The interaction also determines when the nutrients will be made available for plant uptake. Much information is being generated overseas about the role of soil physical structure (e.g. soil aggregation and pore structure) in the relationship between soil flora and microfauna (protozoa) and the consequent impact on soil nutrient availability (Darbyshire, 1994). Other research is being conducted on the importance of timing of crop residue inputs on the succession of microbial predator – prey relationships and nutrient return in annual cropping systems, but there is little research on the interaction of the three factors (synchrony of nutrients, soil structure and availability of carbon) in particular in pasture systems. Support for research in this interdisciplinary area between soil science and soil ecology should significantly improve our understanding of the potential to improve nutrient availability through microbial functions. This may then be managed to the extent that the timing and extent of tillage and grazing as well as other pasture inputs can be optimized.

Recommendations:

1. Determine the effect of tillage / soil disturbance in the cropping phase of pasture / cropping systems on biology in the pasture phase (see **Recommendation D1** and section 4.1.2).

2. Determine whether soil biology can play a role in pasture renovation (**Recommendation G2** and section 4.2.1).

3. Determine the effect of soil physical disturbance on nutrient release in relation to plant requirement (Can we synchronize biological nutrient mineralization to plant requirement?) (**Recommendation C4**).

4.1.2 Rotation with Cropping (Pasture - Crop Systems)

Unlike the annual cropping systems, pastures are mixed plant systems, both within the pasture phase and certainly in pasture-crop systems. Even though the main aim of farmers is to develop or maintain a pasture that has sufficient legume plant component, it is understood that as a broad generalization legumes generally comprise ~30% of plant composition in pastures in southern Australia. Even in well-maintained legume pastures, non-leguminous weeds are known to contribute a significant portion of plant biomass. The effect of crop rotations on soil biota is through the differences in (a) quality of plant residues (i.e. C:N ratio, % lignin), (b) biota associated with a specific plant type and (c) effects of plants on soil physical (e.g. biopores) and chemical properties (e.g. soil pH).

In addition, management practices associated with individual crops (e.g. tillage, fertilizer inputs, agrochemical applications) contribute to the overall impact of crop rotations on soil biota and biological functions (e.g. Goss et al., 1984). A number of studies have reported information on the differences in soil biota or biological functions between cropping, crop-pasture and permanent pasture systems. In most of these studies, the aim was simply to establish or define the differences between the various systems or to determine effects on the cropping phase.

One example of the effect of pasture management on the following crop is the removal of grasses prior to transition to cropping to reduce carryover of soil-borne pathogens to the crop. Research from Dr. Rovira and group from CSIRO Division of Soils in Adelaide clearly demonstrated that management options to reduce pathogen carryover are available, i.e. it is possible to control the incidence of diseases such as Take-all of wheat with the removal of grasses in pastures in seasons before going into the cropping phase. Roget (1996) reported that Take-all control in pastures is an effective option for disease control in low rainfall areas where break crops are not an option. They also indicated that the timing of herbicide application is vital for its effectiveness, i.e. “the earlier the application of the herbicide the surer the results will be”. In addition this favours satisfactory medic growth following grass removal.

Also, disease control following late breaks or dry conditions is not likely to be successful or economic and has the potential to result in very little pasture production or cover. Poor pasture cover following grass removal is a significant erosion risk. In two-year pasture phases, an effective grass control in the first year of the pasture can reduce grass numbers sufficiently in a second pasture year to prevent disease build up. This technique will also improve pasture quality in the second year.

There is currently no similar information for management of soil microbial communities with lucerne in rotations. Even though some of the soil borne pathogens that attack cereal crops have a very broad host range and can therefore also attack the legume and/or grass components of pastures, little work has been done on the impact of crop management on disease incidence during the pasture phase. Nor has much attention been paid to managing crop and pasture rotations to alleviate potential pasture disease problems.

The development of disease suppression at the Avon experimental site (long-term farming system trial) in South Australia has been clearly demonstrated for the cereal phase of the rotations. No detailed assessment of suppression development was made on the pasture phase. However visual observations suggested that significant changes in disease dynamics were occurring. In the initial years of the trial, patches of poor growth (particularly in medic) due to the presence of *R. solani* were regularly observed. These patches of poor growth were estimated to account for up to 30% of the plot area. In later years (after 7-10 years), as the level of general suppressive activity increased, the poor growth patches were no longer evident (David Roget, personal communication). New opportunities exist in this R&D area, as outlined in the section on diseases (**Section 4.3.4**).

Information from both Australia and New Zealand indicates that pastures in rotation certainly improve the populations of earthworms (Smettem et al., 1992). Evidence, mainly from NZ research, indicates increased populations of free-living nematodes and mesofauna in rotations with a pasture phase (Culvenor, 2002). An increase in microbial biomass levels, microbial activity and activities of various soil enzymes in soils from pastures in rotation has been reported for NZ soils (Culvenor, 2002; Francis et al., 2001; Haynes & Francis, 1990). Haynes & Francis (1990) observed improvements in soil N dynamics during pasture phases, whereas the arable cropping phase caused a decline in these biological processes. Little such information is available on the changes in essential soil functions in dryland pasture systems in southern Australia. Most of the improvements in biological functions from rotations with pastures could be attributed to the higher levels of crop residues (roots and litter) during pasture phase. Grace et al., (1995) reported that the higher the proportion of pasture phase in a rotation, the greater the improvements in soil organic matter in a long-term rotation trial at the Waite Institute, SA.

Unlike annual pasture plant species, perennial pasture species such as lucerne (*Medicago sativa* L.) have been shown to increase water use from deeper layers in the soil profile thereby reducing ground water recharge and secondary salinity in southern Australia (Angus et al. 2001; Ward et al. 2002). This increase in water use was observed both within the pasture phase and following crop phase. Improvements in soil chemical characteristics could help benefit biological activity both directly and through improvements to carbon inputs. Lucerne and other perennial pasture plants with deeper roots also have potential to modify N cycling either through higher levels of N_2-fixation (Peoples et al., 1998) or usage of N from deeper layers.

Studies that show differences between pasture and cropping systems are only useful in outlining the benefits or disadvantages of various farming systems, but rarely provide knowledge that would help to devise management options for improved pasture productivity. However, information on the temporal dynamics of key functional groups of biota and biological functions such as Nitrogen mineralization or suppression of plant pathogen survival and their links to pasture composition would help in determining the primary regulators of biotic activities. This would assist the development of management options.

Decisions on the time and nature of transition from pasture into cropping are mainly based on weed management or financial reasons and are rarely made on the basis of future benefits or status of the soil resource. Since pastures have a significant influence on a number of essential biological functions (both beneficial and pathogenic), tools for evaluating pastures for their biological status in relation to the next cropping phase would be valuable for decision-making by farmers (when and how to get out of pasture phase).

The importance of monitoring inoculum levels of pathogens such as the take-all fungus, *Rhizoctonia solani* etc. prior to sowing crops has been demonstrated (Neate, 1994; Roget, 2001) and outcomes of a series of research projects has resulted in a practical commercial outcome in the root disease testing service which is now run by C-Qentec, based in South Austalia with extension across southern Australia.

Information on the status of biota related to carbon and nutrient turnover and overall microbial metabolic status would be required to estimate capacity to supply nutrient, potential for nutrient loss and potential for disease suppression. A better knowledge about the temporal dynamics of various biological processes involved in nitrogen cycling (nitrification, mineralization and immobilization) would also help to reduce the accumulation of excess nitrogen and its role in soil acidification. If we could develop the ability to measure the status of relevant biotic activity and link the measurement tightly to the processes in soil, this would offer new information for farmers to maximize returns from soil biological activity.

The mixed plant composition of pasture systems (annual vs. perennial; legume vs. non-legume), with plant species that occupy different spatial and temporal zones, could allow improved utilization of resources and provide more carbon substrate to biological activities both in terms of quantity and period of availability.

Plant type plays a critical role, both directly and indirectly, because it changes the soil environment and modifies soil biological communities. Therefore a plant-specific approach is better suited for maximizing benefits from biological functions. For example the use of plant species with different rooting patterns, i.e. deeper-rooted lucerne together with shallow-rooted grasses, would provide a rhizosphere environment for microbial growth through a larger proportion of the soil profile compared to plants that occupy a single, smaller range of soil depth (e.g. medic).

Plant type also has a significant influence on the diversity and function of organisms involved in key nutrient transformation processes (e.g. oxidation of sulphur in the rhizosphere of wheat compared to the canola, Grayston & Germida, 1990). Roots modify the turnover of nutrients through their effects on the quality and quantity of root exudates, their water and nutrient extraction patterns and pattern of root turnover.

Plant types differ in the types of microorganisms and microbial and faunal groups associated with their roots and rhizospheres but we only have examples from annual crops at the moment. Thus a mixed plant stand would produce more diverse carbon substrates in the soil and these may be of better quality for sustaining soil microbial activity. Our extensive search in the literature has yielded very little information on the relationship between pasture plant composition and the dynamics of essential functional groups in soil, especially in Australian pasture systems.

Recommendations:

Context:

1. To gain an understanding of the potential benefits from soil biological functions in pasture and pasture - cropping systems, plant species x microbe (biota) x environment interactions need to be considered, instead of concentrating on individual components alone.

2. Lucerne has become widely used in pasture and pasture – crop systems in southern Australia.

3. It is very likely that farmers can benefit more from beneficial soil biological activity (e.g. disease suppression, nutrient cycling).

Research:

1. Assess biological constraints associated with lucerne in rotations in regions or soils where performance has been poor, then develop management to overcome constraints & capitalize on benefits from including lucerne in rotations.

2. Pathogen dynamics and severity of diseases in the pasture phase of pasture-crop rotations, with emphasis on pasture grasses, to manage pasture productivity (**Recommendation E1** and section 4.3.4).

3. **Management of the transition from crop to pasture**:

   In the establishment of pasture, seedling establishment and growth are important (e.g. pathogen and nutrient status of soils). Develop measures of the status of key soil biotic activities in the transition from crop to pasture, to determine the impact of cropping phase management (e.g. nutrient cycling and availability, disease suppression. This is to provide information for farmers to maximize benefits from improved pasture soil biology. (**Recommendation D1).**

4. **Management of the transition from pasture to crop**:

   Development of methods to evaluate a pasture soil prior to the next crop. Pastures provide biologically-based benefits and restrictions for the next cropping phase. For example, knowledge on disease potential, disease suppression potential, nutrient supply potential and soil aggregate stability at the end of a pasture phase will assist in deciding management practices for the next crop. (**Recommendation D2**).

4.1.3 Management of carbon inputs and soil organic carbon

As the majority of soil biota are heterotrophic, i.e. dependant on carbon for energy source, the availability of carbon significantly influences the levels of biological activities in soils. Amounts of biologically available carbon are generally low in Australian agricultural soils, both under pasture and in annual cropping. Traditional management practices involving crop stubble management (retention vs. burning), tillage, intensity of grazing etc have been shown to cause a significant decline in soil carbon status, in particular biologically available carbon or labile carbon (Dalal and Meyer, 1986; Gupta et al., 1994; Grace et al., 1995; Dalal and Chan, 2001). The negative impacts of conventional tillage practices on soil carbon levels, both total and labile pools, have been clearly demonstrated from all cropping regions of Australia (for discussion on mechanisms of tillage effects see **Section 4.1.1**).

Similarly, there is evidence for the benefits from stubble retention to soil organic status, in particular biologically available carbon pools (Dalal, 1986; Gupta et al. 1994). In most cases such information has mainly been to demonstrate evidence for changes in soil carbon levels between farming systems, e.g. pasture vs. cropping. Using the data from a long-term trial at the Waite Institute, Grace and Oades (1994) reported that the number of years of pasture in a pasture-crop rotation had a significant influence on the soil organic carbon levels since the cropping phase is usually associated with loss of carbon and any improvements in carbon levels are mainly attributed to the pasture phase. These improvements from pastures in pasture-crop rotation systems in organic C (labile or total) is also attributed to the improvements in microbial properties such as microbial biomass, microbial activity, bacterial functional diversity (catabolic diversity) and populations of soil micro- and mesofauna (Grace et al., 1994; Degens et al., 2000; Haynes, 2000; Gupta VVSR, van Vliet P. and Abbott, L. Report to GRDC).

Recent evidence suggests strong links between the seasonal availability of carbon (carbon turnover) and soil biological functions such as pathogen survival, disease incidence/suppression and nutrient availability in the annual cropping systems (Gupta and Neate, 1999; Roget D, report to GRDC). Based on our understanding of biological activity and the effect of environmental factors in Australian agricultural regions it is hypothesized that temporal dynamics of carbon turnover has a strong influence on efficiency of nutrient inputs (nutrient mineralization vs. loss). Research in the Mallee Sustainable Farming Project (MSFP) in the low rainfall mallee strongly supports this link under the intensive cropping systems (Gupta and Roget, unpublished). Wardle et al. (2001) reported that management practices that resulted in greater addition of basal resources (i.e. vegetative ground cover, litter inputs and stubble retention) stimulated soil microflora and microbially-mediated processes. Improvements in soil carbon would also benefit aggregate stability and soil structure (i.e. habitable pore space for soil biota) (Adem and Tisdall, 1984; Sparling et al., 1994). Despite this strong evidence between biologically available carbon (BAC) and other biological functions, very little is known on the temporal dynamics of BAC and its influence on the populations dynamics of different functional groups of soil biota and essential biological functions (e.g. nutrient mineralization, beneficial vs. pathogenic microbes etc) in dry land pastures in southern Australia. Since grazing has a significant influence on carbon inputs in pastures (details in later sections) the impact of grazing management on carbon availability and its effect on biological functions requires immediate attention.

Changes in carbon turnover and benefits in soil carbon through management practices in pastures and cropping systems have implications for soils as carbon sinks (Conant et al., 2001). Therefore management practices such as grazing intensity and type and soil disturbance could potentially determine whether soils under pastures act as a sink or source of greenhouse gases.

As discussed before, carbon availability dictates the short-term dynamics of biota and biological functions and plants impact on BAC through rhizosphere and crop residue quality. Genetic modification of plants to incorporate useful traits is a powerful technology that is important for the future development of sustainable (both production and environmental aspects) agriculture systems. Genetically modified (GM) crop varieties promise a number of agronomic benefits and provide management options for Australian crop growers and pasture producers. Genetic modification of plants modifies rhizosphere exudation and crop residue quality (at least in some examples). Future research on potential non-target effects of these new plant varieties and associated agronomic practices on soil biological functions is one of the key factors for their sustainable incorporation into Australian agricultural systems.

Recommendations:

Context:

1. Carbon availability is one of the key drivers of biological activity in Australian pastures (dryland). Many management practices that are followed in Australian pastures have impacts on soil carbon status especially biologically-available carbon.

2. Greenhouse gases: improved pastures, with greater soil C "storage" capacity and reduced methane and nitrous oxide emissions, may be used beneficially in carbon trading.

Research:

1. Determine the temporal dynamics of carbon availability (seasonal, field-based, comparing management regimes within pasture & pasture/crop systems) and links to essential biological functions (depending on region, different factors will be more important: nutrient mineralization and loss, pathogen survival, pesticide degradation, aggregate formation). Management regimes include grazing systems, pasture renovation and soil ameliorants. (**Recommendation B1**).

2. Determine the impact of grazing management on carbon availability and its effect on biological functions (see **Recommendation B1** and section 4.2.2).

3. Determine the role of grazing management in C dynamics in relation to soils as carbon sinks and global greenhouse gas budgets. Research in the USA is far ahead of Australia, and we cannot import these results. (**Recommendation B2**).

4. For key soil microbial processes (e.g. mineralization of N or development of disease suppression), define the number of microbially-optimal days based on conditions (soil type and soil moisture & temperature, based on weather data) found in different agro-ecological zones). **Aim**: to provide information for prediction of soil biological function (**Refer to section 2; Recommendation B3**).

4.1.4 Inputs (fertilizer / ameliorants)

Soil organisms are the driving force for a number of biological processes that transform nutrients into plant-available forms and they therefore contribute to soil fertility. Soil organisms also help in the uptake of nutrients by plants, e.g. phosphorus and Zn uptake is aided by the mycorrhizal fungus-plant symbiosis. Despite the availability of fertilizer-based nutrients for farmers' use, it is evident that biota-mediated nutrient mineralization processes play a key role in maintaining the plant available nutrient pool in soils (both economic or environmental reasons), especially in the low input based farming systems of the dryland cropping zones in Australia. For soil organisms to be effective suppliers of essential nutrients to plants, they not only need carbon and nutrient sources for their growth and a mineralizable nutrient source (organic matter) but also require suitable soil physical and chemical conditions that support their activity.

There may be an adequate supply of carbon for biological activity both in the rhizosphere and near crop residues but the availability of essential nutrients (e.g. nitrogen, trace elements) may not be adequate with crop residues, in particular cereal crop residues and litter from pasture grasses. Therefore the addition of inputs such as fertilizers, both organic and inorganic, and soil ameliorants that increase root growth will increase the crop growth and the rhizosphere effect, thereby increasing crop residues or litter. This will increase the overall populations of soil biota and their level of function (Fraser et al., 1994; Ross et al., 1995; Olsson et al., 2002). Surface-applied organic matter, along with subsoil modification on a red brown earth in northern Victoria has resulted in increased earthworm numbers in a mixed ryegrass and clover pasture (Olsson et al., 2002). In this irrigated pasture, soil modification along with addition of chemical or organic matter inputs led to increased pasture production, but the benefits in the second year were less than that in the first year after modification. Greater pasture yields and increased earthworm numbers were mainly attributed to improved soil aeration and better functioning of roots. Despite the demonstration of benefits for pasture production due to soil modification and addition of inputs, the authors indicated that the actual mechanisms for the yield benefits were not clear. Differences in N nutrition, change in pasture composition, and lack of root length for perennial ryegrass were some of the reasons listed by the authors (Olsson et al., 2002).

In alkaline calcareous soils, application of micronutrient inputs (e.g. Zn, Mn) may be necessary in order to improve pasture production through reducing disease incidence or increasing N_2-fixation by pasture legumes (Thongbai et al., 1993; Wilhelm et al., 1990).

It is known that improved soil physical properties (aeration and therefore habitable pore space) can modify microbial activities and the populations of various soil biota, both beneficial and pathogenic. Even though initial increases in pasture production due to soil modification can be explained from general soil physical properties, longer-term effects on pasture growth are linked with overall changes in the whole soil (soil physical, chemical and biological properties). Thus this work (Olsson et al., 2002) clearly demonstrates the need for an integrated approach and that work on biological function needs to be included in order to best develop management options that involve soil modification and addition of inputs.

Results from both regenerating and sown pastures in various agro-ecological zones in southern Australia indicate that the addition of fertilizers, e.g. P and Zn, increased pasture dry matter production. For example, average results over 15 sites in regenerating medic pastures under the ‘Medic decline project’ resulted in a 25% increase in dry matter production (Bellotti, 1998a). Addition of inputs that promote plant growth without causing negative effects on soil physical and chemical properties has the potential to promote soil biota and their activities. Increased pasture dry matter production could result in improvements in biota populations and biological activities in systems where there is a low level of labile organic matter for biota requirements, e.g. low fertility soils in the dryland pastures of southern Australia. Fraser et al. (1994) reported higher levels of microbial biomass, enzyme activities and earthworm populations in a grazed pasture, that was supplied with superphosphate annually in the Canterbury region of NZ. Wardle et al. (2001) observed improvements in soil microflora and microbially-mediated processes as a result of practices that improved ground cover.

Information on the direct effects of fertilizer inputs on soil biological functions in the field is not available, especially for pasture systems in Australia except for mycorrhizal fungi and the *Rhizobium* symbiosis. Results from overseas suggest that the application of organic fertilizers can significantly modify biological properties (e.g. microbial biomass, microbial activity, soil enzyme activities, nematode, collembola and earthworm numbers) but the effects of inorganic fertilizer addition are variable. Namdeo and Dube (1973) found that application of urea increased urease activity but reduced proteinase activity. It is necessary to link the changes in biological properties following fertilizer inputs to changes in soil physical and chemical properties in order to understand the mechanisms of change and to predict the impact, if any, of long-term application.

One example of the effect of fertilizer addition on biological processes is symbiotic nitrogen fixation. It is known that nitrogen fixation by the legume-*Rhizobium* symbiosis is decreased in the presence of higher levels of available nitrogen in soil. Information on the effects of P and micronutrient fertilizer inputs on nitrogen fixation by legumes clearly suggests that it is necessary to maintain the availability of adequate levels of these essential nutrients in order to gain full benefits from symbiotic nitrogen fixation by pasture legumes.

During the last decade or more there has been a steady decline in inputs (e.g. P fertilizer) added to pastures in dryland regions of southern Australia, in particular in pasture-crop rotations. The resultant decline in pasture dry matter production has not only reduced benefits from nitrogen fixation by pasture legumes but also resulted in a decline in associated biological functions that depend upon the pasture dry matter, both in terms of quantity and quality, as a source of carbon and nutrients. Recent trials in the Mallee Sustainable Farming Program and some long-term trials in southern Australia clearly show that addition of fertilizer inputs (e.g. P, Zn) benefits soil biological functioning both in the pasture phase and the following crop period. However, no detailed information is available on (a) the true changes in critical functional groups of soil biota and (b) the nature and extent of benefits in biological functions (e.g. level and duration of improvements in nutrient availability), which are necessary to develop new management options that could be recommended to farmers.

Some of the major reasons for reduced nodulation and nitrogen fixation by subterranean clover in acid soils include (a) lower numbers of *Rhizobium trifolii*, (b) poor colonization of more acidic regions of the soil profile and (c) *Rhizobium* sensitivity to nutrient imbalances such as Al toxicity and Ca deficiency (1988). Addition of soil amendments, such as liming of acid soil, improved nodulation of pasture legumes as shown by experiments in acid soils at a number of places in southeastern Australia. Richardson et al. (1988) found that restrictions to nodulation associated with low soil pH were largely compensated by the plant, i.e. either through distribution of a large proportion of nodules in less acidic regions or through changes to nodule size in different regions of the root system thereby keeping total nodule mass per plant the same. However such compensation in nodule number by pasture plants may not maintain the overall level of nitrogen fixation.

Soil pH has been shown to affect the growth of fungi including pathogenic fungi. The responses of plant pathogenic fungi to changes in soil pH are due to many factors including elemental toxicities, availability or lack of nutrients and the susceptibility of plants to pathogen attack. Barbetti (1990) studied the effect of added lime on the pathogenicity of root pathogens of subterranean clover and found that different root pathogens responded differently to the addition of lime and that there were interactions between lime and cultivar and lime and pathogens. For example, addition of lime reduced the severity of disease on tap and lateral roots by *Fusarium avenaceum* but *Pythium irregulare* had a tendency to become more pathogenic. This study clearly demonstrated that it is useful to know the effects of soil ameliorants on the growth and disease-causing abilities of pathogenic fungi, in order to gain full and long term benefits from such management practices. It should be noted that Take-all in wheat can be exacerbated by liming acid soils (Coventry et al., 1989) but little is known about the effect of liming on diseases of pasture plants in different soil types. In addition, it is evident that future soil biology research should consider the interactions between soil organisms, their soil habitat and the plant along with the environmental factors that dictate the importance of each of these components.

Information on the effects of soil ameliorants on pathogens and disease incidence on pasture grasses is very limited; making it one of the important areas of future research.

Other than the specific microbial groups mentioned above and earthworm populations, very little information is available on other important functional groups of soil biota and their activities e.g. microbiota involved in nitrogen mineralization. Many biological functions in agricultural soils are influenced by a variety of functional groups of microflora and trophic groups of soil fauna. It is therefore necessary to understand the dynamics of these biota components following the addition ameliorants, both to gain maximum long-term benefits and to be able to predict the extent and duration of potential benefits.

Recommendations:

Context:

1. An integrated approach is needed: in order to develop best management options that involve soil modification and addition of inputs, work on biological function needs to be included.

2. During the last decade or more there has been a steady decline in fertilizer inputs (e.g. phosphorus) added to pastures in dryland regions of southern Australia, but increased inputs are likely to stimulate soil biological activity (with associated future benefits) as well as plant growth.

3. Little is known about the impact of liming on pasture plant disease in acid soils (although large interactions are known for cereal diseases).

Research:

1. Determine the full beneficial effect of pasture fertilizer inputs on soil biological activity (both the extent and duration of change in biological function), both directly and via improved plant growth. Consider this research together with determining the benefits of greater carbon inputs (**Recommendation G1**).

2. Determine the effects of soil ameliorants on pathogens and disease expression on pasture grasses (little knowledge for grasses compared to legumes).

4.1.5 Pesticides (nematicides, herbicides, fungicides, antihelminthics)

The use of one or more types of pesticides may be necessary both to keep a healthy and productive pasture for grazing and to capture the full benefits of the pasture phase in a pasture-crop rotation.

Herbicide use is a necessary practice to maintain a desirable plant composition in a pasture, i.e. to remove weeds and / or hosts of plant pathogens. Herbicide use is recommended and actively encouraged to remove grasses in pastures prior to going into a crop phase in order to reduce the pathogen inoculum for the following crops. A number of fungicides have been tested to reduce the negative impacts of fungal pathogens in pasture crops especially seedling rots (Falloon, 1985; Skipp, 1986). Similarly, application of nematicides and insecticides is practised to reduce damage caused by plant parasitic nematodes and insect pests such as red legged earthmite. Thus the use of one or more types of pesticides is often necessary to maintain a healthy pasture.

The herbicides that are known to persist for more than one season, e.g. sulphonyl urea (SU) herbicides used in crops, are known to have residual effects on pasture plant species during the following pasture phase. The effects of SU herbicides on pasture plant growth may be easy to identify but the non-target effects of residual herbicides on plant-microbe interactions has been difficult to identify.

As herbicide use has become a vital component of modern agriculture, in particular under reduced till systems, it is necessary to understand both the direct effects of residual herbicides on pasture plant growth and also their non-target effects on pasture plant-biota interactions. It is assumed that, because of inconsistent reports on any significant negative effects of long-term herbicide use, herbicides would not constrain biological functions in agricultural soils. This may be true for a number of groups of biota. However, effects of herbicides on micro-organisms are commonly tested on individual populations or on a specific biological activity rather than on soil populations and soil biological activities. Population changes are difficult to interpret and do not indicate a function; in particular, short-term dynamics in biota populations can be interpreted simply as background temporal dynamics.

Recent evidence suggests that short-term disturbances in either the population or function of specific groups of soil biota due to some herbicides may be impeding their proper functioning (Gupta and Neate, 1997; Gupta, VVSR report to Land and Water Australia 2002). Such impacts may not show any long-term negative effects but could reduce the effectiveness of biological functions in particular plant-biota interactions. For example, fungicides recommended to control plant pathogen activity could potentially affect general soil fungal activity and thereby reduce soil biological activities such as P-uptake or aggregate formation. The use of fungicides to control plant diseases, may be better targeted provided that information on their non-target effects is available.

Non-target effects of herbicides can be either positive or negative. Non-target negative effects of herbicides on soil biological activities may (a) cause undesirable effects on essential nutrient cycling (e.g. reduced nitrification and N mineralization, N2- fixation, nutrient uptake efficiencies of plants) or (b) promote the growth of deleterious micro-organisms (plant pathogens) resulting in unexpected damage to crops through increased diseased incidence. (Wardle et al., 2001; Ramsay, 1984; Namdeo and Dube, 1973). Information on the effects of herbicides on macrofauna (e.g. earthworms) suggest that some specific herbicides may have negative impacts. For example, Dalby et al. (1995) found that the activity of earthworms was reduced when there was a direct contact with the chemical during herbicide spraying. Such information would be useful in designing herbicide spray schedules to avoid spraying during the peak earthworm activity on the soil surface.

Herbicides recommended for use in legume crops are reported not to affect the growth of *Rhizobium* spp. directly. However, recent evidence suggests that some of these herbicides may disturb the legume-*Rhizobium* symbiosis resulting in the N_2-fixation potential of the legume crop not being realised (Gupta and Roget, unpublished data). Similarly, residual concentrations of sulphonyl urea herbicides, which may not reduce the growth of a legume crop, could inhibit N_2-fixation. Such effects might not restrict the productivity of a legume crop per se but could reduce the nutritional benefits of a pasture both for the grazing animal and to the following crop phase.

Effective management of herbicides that cause reversible inhibitions is difficult, because reaching a balance between high herbicide efficiency and minimum non-target effects requires a better understanding of herbicide-microorganism-environment interactions. Future research on the non-target effects of herbicides on specific biological functions and plant-microorganism interactions has great potential to maximize benefits from pasture biological functions.

A variety of micro-organisms have been shown to be capable of degrading different types of pesticides (e.g. herbicides, insecticides, fungicides). Micro-organisms play a key role in the degradation of specific herbicides thus reducing their persistence in soil and allowing us to grow susceptible crops in the following season. Micro-organisms that degrade herbicides selective for specific crops have a great potential to improve crop rotation options through degradation of unwanted chemicals in the rhizosphere (this is related to the more general concept of phytoremediation). The ability of microorganisms to degrade many types of chemicals is one of the main reasons for the limited life of chemicals in soil and the ineffectiveness of some herbicides in some soil types.

The use nematicides to control plant parasitic nematodes in pastures may not be a common practice, however the actual extent of nematicide use in Australian pastures in the different agroecological zones is not clearly known. Nematicides such as Oxamyl and Phenamiphos have been reported to control plant parasitic nematode damage in pastures (Orchard 1984; Ramsay, 1984). Plant parasitic nematodes are only one of the components of total soil nematode population and the role of free-living nematodes in certain soil biological functions has been established in pasture systems overseas. Nematodes contribute to 60% of overall soil biota in permanent pasture soils in WA. Even though the total populations of free-living nematodes showed little seasonal fluctuation, lack of optimum soil moisture would restrict their activity during large periods of the year. Bacterial-feeding nematodes were the major group of free-living nematodes in WA and this is similar to observations in cropping soils in southern Australia. The presence of large populations of nematodes in the dryland pasture systems suggests greater potential for their contribution to soil biological functions during periods of optimal environmental conditions, i.e. after rain.

Information on the effect of nematicide use, both short-term and long-term, on the populations and activities of other trophic groups of nematodes in Australian dryland pasture soils is not available. Similarly, there is no information on the non-target effects of nematicides on soil microflora and biological functions in Australian pasture systems. Reports from NZ show varying effects of Oxamyl and Phenamiphos on soil microflora (bacteria, algae and actinomycetes; Ramsay, 1984; Orchard, 1984). Application of nematicides such as Oxamyl and Phenamiphos appear to have reduced the numbers of nematodes and earthworms in NZ pastures (Yeates, 1984; McColl, 1984 quoted by Orchard, 1984).

The interactions between different trophic groups of nematodes and between nematodes and other members of the soil food web have the potential to contribute to a number of beneficial biological functions in the soil and the rhizosphere. Therefore information on the effects of nematicide use on the activity of free-living nematodes is necessary to exploit the full potential of soil biota in the low input pasture systems.

Since the 1970's the use of antihelminthics in the Australian livestock industry has increased steadily, and the broad-spectrum ivermectins and milbemycins (macrocyclic lactones) have been widely used, with great effect, for more than a decade. Available information on the effects of macrocyclic lactones (e.g. ivermectin, moxidectin) on soil fauna suggest that these chemical residues in dung can cause detrimental effects on dung-inhabiting flies, arthropods (Coleoptera and Diptera), and invertebrates such as earthworms (Sommer et al., 1992; Wardhaugh et al., 1993; Strong and Wall 1994; Gunn and Sadd, 1994; Svendsen and Baker, 2002). Results from controlled environment studies are either negative or show no significant effects i.e. not conclusive.

Most of the studies on antihelminthics have not investigated the long-term effects on reproduction and fauna mediated biological functions in field situations. For example, the rate of removal of dung from the soil surface could influence the quality of water moving through catchments and thus even short-term effects of chemicals on dung beetle activity could impact on catchment-level function. In contrast to controlled environment studies, where the fauna are tested under optimal conditions, soil fauna in the field are exposed to greater stresses including variable environmental and nutritional conditions. They may therefore be more sensitive to agro-chemicals. In addition, these studies should be done at realistic chemical concentrations, taking into consideration the effects of drug formulation and the type of dung. Such information could help the development of options for strategic use of antihelminthics that takes account of the seasonal activity patterns of dung beetles.

Recommendations:

Context:

1. Long-term persistence of some herbicides in some soil types can be detrimental to pastures (increased disease expression and reduced N fixation).
2. Fungicides to control disease may affect other soil biological processes mediated by fungi (eg P and micronutrient availability).
3. Specific herbicides may have negative impacts on earthworms if used inappropriately.
4. Some herbicides may disturb the legume-*Rhizobium* symbiosis, resulting in the N_2-fixation benefit of the legume crop not being realised.

A new generation of herbicides has recently been developed.

Research / extension:

5. Determine the non-target effects of **new** herbicides on specific biological functions and plant-microorganism interactions. Manage the interactions to allow maximum benefits to be gained from pasture soil biological functions. **Aim:** to make recommendations on pesticide use to farmers. (Recommendation F3).

6. Determine the impact of other most commonly used agricultural chemicals (fungicides, nematicides, insecticides) on key soil biological activities (nutrient mineralization and uptake, disease expression). **Aim:** to make recommendations on pesticide use to farmers. **(Recommendation F2**).

7. Design herbicide spray schedules to avoid spraying during peak earthworm activity at the soil surface (extension activity).

4.1.6 Irrigation: input of water

This review focuses mainly on dryland pasture systems. However we have included a small section to indicate that irrigation management strongly influences pasture growth, soil structure and soil biological activity. Irrigation-induced increases in pasture growth resulted in increased earthworm activity. Management practices, i.e. removing subsoil constraints, organic matter addition, deep ripping etc, that promote the growth of irrigated pastures results in increased earthworm activity (de Bruyn et al., 1997).

Recommendations:

Context:

There is little or no information for southern NSW, Victoria and SA on links between irrigation scheduling, nutrient turnover (mineralization vs immobilization therefore availability vs. loss) and microbial activity. Existing knowledge from northern NSW and WA will not be applicable.

Research:

1. Field-based research to determine the effect of irrigation scheduling on the interaction between soil biotic activity, habitable pore space and fertilizer inputs. **Aim** to develop recommendations about relative timing of irrigation and nutrient inputs so that farmers can gain greater benefits from soil biological activity and increase efficiency of nutrient use (as well as reduce negative offsite impacts).

2. Determine effect of soil microbial activity on the dynamics of pathogenic microbes in soil, in particular during periods of flush in microbial activity after irrigation.

4.2 Grazing management

4.2.1 Impact of grazing management on pasture growth and soil biota

Grazing management impacts on soils in a number of ways. The intensity of stocking and the type of grazing management regime influence the soil physically, chemically and biologically.

Greenwood & McKenzie (2001) reviewed the literature on the effect of grazing on soil physical properties and pastures. Their schematic diagram showing interactions in the soil in pasture systems is quite similar to our Figure 1. In this review we focus more on the aspects that they did not cover, i.e. the interactions between the soil organisms, pasture plants and grazing management.

Greenwood & McKenzie (2001) stated in their review that “grazing adversely affects soil physical properties”. They also conclude that the effects are greatest at the soil surface and with heavier stocking rates, and that wet, cultivated soils are most at risk of degradation. The result is that poor soil physical conditions can reduce pasture productivity. We suggest that some of this effect may be caused by the increased activity of soil-borne pathogens, since some are favoured by high water content (e.g. Oomycete fungi such as *Phytophthora* and *Pythium*).

Temporary removal of stock from soils that have a very high water content (after opening rains or after irrigation) can reduce compaction damage (Greenwood & McKenzie 2001; Proffitt et al., 1993; de Bruyn et al., 1997) and this will assist the maintenance of soil biological activity. The use of irrigation scheduling has good potential to improve soils on irrigated pastures (de Bruyn et al., 1997).

In a sheep grazing field trial in WA, deferring grazing for several weeks after opening rains (compared to continuous grazing) helped to reduce compaction damage, i.e. water infiltration rates were not reduced. Bellotti (1998b) found that in pasture-crop rotations, heavy grazing of medic pastures (a) did not affect total pasture production but (b) “resulted in poor surface soil structure and poor seedbed conditions” and (c) increased the inorganic mineral N levels present at the time of sowing for the following wheat crop.

In terms of improving the condition of degraded pasture soils, Greenwood and McKenzie suggested that some type of cultivation or soil disturbance would normally be needed to improve soils. However, in a different approach, Mapfumo et al. (2000) assessed the ability of grazing practices (heavy, medium and light stocking rate) to alter soil physical and chemical properties in a 3-year study in Alberta. They observed only small changes in water holding capacity, soil N, soil pH and EC, but suggested that their study may have been too short term to detect larger changes in the particular soil type that they studied.

Our opinion is that changing grazing management still warrants investigation as an option to improve soil conditions. Changed grazing management could improve soil conditions via greater input of organic matter, which would generally be expected to increase soil biological activity. Research could be done to compare physical disturbance with changed grazing management in pasture soil renovation.

Much of the work on grazing-related influences on soil biological properties has focused on the effects on macrofauna (such as earthworms) and there is limited or no information on other biological properties. Future work on grazing impacts on soil biota and soil biological functions via changed soil physical properties should link with changes in the availability of carbon and habitable pore space and therefore microflora and microfauna. In addition, as the quality and quantity of carbon inputs influence the composition of soil microflora (e.g. bacteria vs. fungi, non-symbiotic nitrogen fixation) and thereby potentially modify soil food-web dynamics, grazing-induced changes in carbon inputs (both above ground litter and below ground root turnover) and their effects on biological functions require future research. Such research would help develop grazing options for better utilization of benefits from carbon inputs in pasture systems.

Environmental impacts of grazing management: the potential off-site impacts of management practices are worthy of consideration due to concerns about wider landscape degradation and water quality. A simulation study (Simpson et al., 1998) on the predicted impact of grazing management on water movement through the soil profile concluded that shifting from annual to perennial pastures at some locations (winter-dominant rainfall areas) substantially reduced water drainage through the soil profile.

Recommendations:

Context:

Future work on grazing impacts on soil biota and soil biological functions via changed soil physical properties should link with changes in the availability of carbon and habitable pore space and therefore microflora and microfauna (previous work has focused on macrofauna).

Research:

Pasture renovation to overcome soil compaction problems: compare the effect, benefit and cost of two contrasting approaches, i.e. soil physical disturbance versus changed grazing management, in different regions, for their ability to improve pasture soils (including biological status) and pasture productivity. (**Recommendation G2**).

4.2.2 The impact of grazing management on plant roots, and implications for soil biological activity

Can soil be improved via better pasture management? Gardiner and Kawabe (1983) described the results of a pasture improvement program in NSW that used aerial sowing and improved water and grazing management. They stated that “the pasture improvement program and judicious grazing management resulted in greater ground cover and pasture yield; better pasture root growth and higher organic matter accumulation … characterize improved soil conditions”.

Various authors have described the principles of controlled grazing (eg Pratt, 2002). A key point is that when pasture plants have been severely grazed, their re-growth is likely to be slower. The concepts of (a) grazing more lightly and (b) resting pasture between grazing periods, to allow recovery and re-growth, have considerable implications for not only for the pasture plants but for soil biological activity under pastures. This is because most of the biological activity occurs in the rhizosphere and around decaying organic matter, and the root growth of plants that have been lightly grazed and then rested will be much greater than that of heavily grazed pasture plants.

There has been considerable debate over the benefits of different types of grazing management in terms of their effect on pasture and stock productivity, and on soil conditions. In a progress report on their study, Waller et al. (1998) reported that tactical stocking (a variation on rotational stocking) led to greater pasture production and reduced need for supplementary feeding in ryegrass / sub clover pastures in southwestern Victoria. In a later paper (Waller et al., 2001) they reinforce these conclusions but also stated “pasture improvement and soil fertility status have a much greater impact on productivity than changes to grazing method”.

The connection between grazing management and soil biological activity is that it heavily influences the supply of “food” to the soil organisms both in terms of amount and timing. Soil organisms derive their food from the rhizosphere, from decaying soil organic matter and from litter and dung that either remains on the soil surface or is transported downwards by earthworms or dung beetles.

Grazing pressure is one of the main controls on the amount of plant litter present in a grazing system and on the amount of plant root growth (with its associated carbon exudation in the rhizosphere). Overgrazing reduced litter and root production in a semi-arid grassland (Christie, 1979). Christie recommended that the relationships between the production of herbage and litter and soil nutrient cycling should be studied within the grazing system. It appears that this type of research is still required and is important in helping to determine the requirement for nutrient inputs.

There is evidence that the root growth of annual pasture plants responds differently to stocking rate than does the root growth of perennial species. Doyle and Sharkey (1976) showed that under increased sheep stocking pressure, the root growth of barley grass and sub clover remained vigorous. They noted, however, that for “perennial pasture species…root development and root branching may be expected to decline with increase in grazing pressure”. This is important because there appears to be a trend towards greater proportions of perennial plants in grazing systems in southeastern Australia.

The physiology of the pasture plant’s response to moderate to severe defoliation (simulated grazing) was comprehensively reviewed by Richards (1993). The effects of moderate to severe loss of foliage varied with the developmental stage and the growth rate of the plant. For a variety of C3 and C4 grasses, root growth of rapidly growing plants was very sensitive to defoliation and was quickly reduced (with hours or a few days) after substantial loss of foliage. Nutrient uptake was also rapidly decreased. However for slow-growing plants, the effect was much less or was even reversed.

The term “pasture decline” can have different meanings. For many producers, it means invasion of pastures by weeds leading to undesirable changes in species composition. However, decline in growth rate, which can be caused by soil-borne disease is also termed pasture decline (Bellotti, 1998a; Stovold, 1974; Burnett et al., 1994). Reeve et al. (2000) reported from a farmer survey that pasture decline was most frequently assessed as being due to weed infestation. Lower pasture production and lower pasture vigour were ranked as 3 and 4 in causes of pasture decline.

Depending on the situation, soil biological effects such as soil-borne disease and nutrient loss can be a major reason for this latter type of pasture decline.

Amount of plant re-growth following previous grazing has been suggested as a practical way to decide when to resume grazing (Fulkerson and Donaghy, 2001). This method is a surrogate for the level of stored soluble plant carbohydrates. As an example, Fulkerson and Donaghy suggest that for ryegrass pasture the three-leaf stage of regrowth is a minimum level of regrowth before resumption of grazing. Grazing of ryegrass at the 2-leaf stage slowed down regrowth and reduced grass persistence. The importance of this concept for soil biological activity is that if grazing is scheduled using plant growth as an indicator this will very likely also improve the persistence and activity of soil biological processes which rely on plant materials (litter, rhizosphere exudates, decaying roots) for food. The involvement of the rhizosphere - the exudates, microbial activity and the associated nutrient cycling should also be taken into account. Interactions with root diseases may complicate the situation. This is a potential area for useful research.

Grazing management has direct impact on soil biological activity through the amount of litter and root material present on or in soil. Mapfumo et al. (2002) in a study on Canadian prairie pasture grasses found that litter C and N pools were lower with increased grazing pressure. The size of the soil C and N pools will control soil biological activity to a large extent, but Mapfumo et al did not address the microbiology of their study system.

Grazing systems based on rotational or pulsed grazing will allow pasture plants to re-grow between grazing. This is advantageous because it is likely to maintain a higher root biomass (Jones 2002) and this would be expected to lead to higher soil biological activity.

Svejcar & Christiansen (1987) studied the influence of cattle grazing intensity on root dynamics of a pasture grass in the Great Plains in the USA over three seasons. Root mass and root lengths were substantially reduced (by 27% to 46%) in the heavy compared to the light grazing regimes. However, not all studies have reported that grazing intensity dramatically influences root dynamics. Matthew et al. (1991) studied ryegrass root dynamics in a 12-month field-based study in New Zealand. They reported that root production and root mass were reduced by approx 10% by high compared to low sheep grazing pressure. These researchers criticized a number of studies that had been done previously using pot trials and young seedlings (Evans, 1973).

A very interesting and relevant recent paper from the USA (Hamilton and Frank 2001) has described how grazing might lead to greater nutrient availability in the rhizosphere via stimulation of biological activity. Their study, which was done in a controlled environment using the grazing-tolerant grass species *Poa pratensis*, showed that grazing (clipping) of the grass stimulated rhizosphere exudation and this increased exudation was taken up by the rhizosphere microbial flora. There was a positive feedback whereby more N was mineralized by the microbial flora, and this N was then taken up into the plant. Thus their concept is that grazing (or at least clipping in their controlled system) promoted plant regrowth. The validity of this concept would need to be tested in the field using different grazing pressures and grazing management. It is probable that this kind of positive feedback would only operate within a certain range of grazing pressure and that overgrazing may not give this type of benefit.

We recommend that research be directed towards the following aim: decision support for grazing options (timing and intensity) that consider not only plant growth and re-growth after grazing, but also composition of the soil biota which could lead to improved biological functions (eg beneficial versus deleterious organisms, nutrient cycling, disease expression or suppression).

Recommendations:

Context:

A trend towards greater proportions of perennial plants in grazing systems in southeastern Australia.

Research:

1. Investigate the relationship between carbon inputs (seasonal, above- and below-ground) and biological processes associated with soil nutrient cycling within a field-based grazing system. **Aim**: to determine the balance between input of nutrients versus nutrients provided by soil biological activity, to gain more benefit eg mineralized nitrogen, also P availability in calcareous soils. (**Recommendation G1, linked to B1)**.

2. Plant re-growth can be used as an indicator for resumption of grazing. Test the link between plant re-growth and soil biological processes, including rhizosphere. Does this method of scheduling grazing also deliver greater benefits from soil biological activity? (i.e. long-term sustainability of soil biological processes such as nutrient cycling). (**Recommendation C1**).

3. *Appropriate grazing pressure could stimulate pasture re-growth via rhizosphere biological processes*.
   Investigate rhizosphere processes over a range of grazing pressures which may lead to positive feedback on microbial mineralization of nutrients and their availability to plants (resulting in more rapid pasture re-growth). (**Recommendation C2).**

4. Different grazing systems and grazing pressures lead to differences in soil biological functions (eg proportion of beneficial to deleterious organisms, nutrient cycling, disease expression or disease suppression). Determine the links between the composition and activity of soil biota under different grazing systems (linking soil biodiversity to function). (**Recommendation C3).**

5. *Minimize nutrient losses from grazing systems, especially in higher rainfall areas.* Determine the role of grazing pressure in soil nutrient loss (especially N, but also P in high rainfall areas). Determine regulators of biological nutrient mineralization and loss, as affected by pasture composition: how can soil biota activity minimise the loss of nutrients from pasture soils. **Aim:** to: recommend grazing management to improve efficiency of resource use & reduce off-site impacts especially in high-rainfall areas. (Inappropriate grazing pressure could result in nutrient loss from the system via denitrification and by leaching). (**Recommendation C5).**

4.3 The soil food web and soil-borne plant pathogens

4.3.1 The soil food web

The different types of soil fauna (microfauna – protozoa and free-living nematodes, mesofauna – collembola and mites, and macrofauna) play a significant role in a number of biological processes related to plant growth and ecosystem function. In contrast to microflora, the effects of soil fauna on essential plant biological processes are less specific, except for pathogenic soil fauna such as plant parasitic nematodes and mites. It is the interactions between microflora and various groups of soil fauna that are critical for a number of biological functions, e.g. nutrient mineralization, disease suppression and survival of introduced microflora. We now need to integrate the interactions between different functional groups of microflora and trophic groups of soil fauna in our efforts to understand, predict and manage soil biota and their essential biological functions.

Research conducted in pastures in WA indicated that micro- and mesofauna contribute ~20% of net nitrogen mineralization (Gupta et al., 1998 GRDC final report). Populations of protozoa and free-living nematodes in southern Australian pastures range between 100-10^6 / gram soil for protozoa and 600-1000 per square metre for free living nematodes (Gupta, VVSR, van Vliet, P. and Abbott, L. report to GRDC 1998). Results from a permanent pasture in South Australia indicated that protozoan activity contributed from 30-50% of net N mineralization and predation by microfauna and mesofauna also have significant roles in the disease suppression phenomenon in pasture-crop rotations at Avon, SA (Gupta and Roper, 1996; Gupta et al., 1999; Gupta and Neate, 1999).

Research from overseas clearly shows that feeding activities of microbial-feeding nematodes can enhance nutrient mineralization and uptake by plants in grasslands (Bardgett et al., 1999). Based on research on the decomposition of litter and roots of a Chihuahuan desert annual, Parker et al (1984) reported that the activity of microarthropods stimulated microbial activity and nitrogen budgets in relation to mineralization and immobilization. Temporal dynamics of decomposition of litter, and the immobilization and mineralization of nutrients are influenced by the activity of protozoa, nematodes and microarthropods and could be linked to time of nutrient availability to plants. Unlike the pasture / grasslands systems overseas (including in NZ), the majority of pasture systems in southern Australia experience quite short periods of optimal moisture separated with long periods of dry soil. Hence it is necessary to understand the environmental regulators of soil fauna activity (other than macrofauna e.g. earthworms) in these systems in order to make use of their activity for plant-beneficial functions.

The constraint of linking a variety of organisms involved in a single process to the process itself was overcome, to some extent, by the introduction of the foodweb concept. In this approach, organisms across trophic levels are linked and the linkage is based on the flow of energy and food preferences. This approach has been used successfully to study (understand and model) changes in organic matter decomposition, e.g. for different crop residues, (a multiple organism mediated function) following changes in management practices (e.g. tillage and pesticide use).

For example, tillage-induced shifts in the fungi:bacteria ratio influence the rate of organic matter decomposition and nutrient availability. That is, reduced till systems support a fungal-based food web (accumulator organisms) where as conventionally tilled systems support a bacterial-based foodweb. Such an understanding of the importance of microbial community composition does help in the management of soil organic matter and nutrient availability in agricultural systems including pasture systems.

A similar approach may be needed to understand the mechanisms behind (a) suppression of plant pathogens in agricultural soils (diseases are a major constraint in Australian agriculture) and (b) carbon sequestration by agricultural soils. The food web approach takes into account temporal dynamics of biota populations, but its current use does not take account of the spatial heterogeneity in biota distribution. For example, the distinction between location of available carbon, e.g. quality and quantity of available carbon including temporal dynamics of its availability, in grazed continuous pastures compared to pasture-crop rotations has not been considered until now.

It is necessary to incorporate these principles of spatial and temporal variability if we plan to exploit the biotic processes for the benefit of pasture production and sustainability of the pasture industry. Temporal aspects of the activity of food web components in relation to grazing management and regrowth of pasture plants has the potential to provide information that would assist in predicting nutrient mineralization hence in the decision making process for fertilizer inputs.

Recommendation:

Context:

Soil disturbance, level of carbon inputs and agrochemical application have significant influence on the dynamics of the soil food web, both in terms of composition and role in specific biological functions. Much of the research is done with annual cropping systems and little is known about pasture systems, in particular in Australian soils and conditions.

Research:

Determine the impacts of grazing management on soil food web dynamics, importance of various trophic groups in different agro ecological zones and links to biological functions. For example, food web dynamics in relation to synchronization of nutrient mineralization with plant demands. (**Recommendations C3, C4).**

4.3.2 Earthworms

From “Managing Earthworms as a Resource in Australian Pastures” by Dr. Geoff Baker (Appendix 5).

Earthworms are the most obvious element of the macrofauna in pasture soils in southern Australia. The earthworm fauna in pastures in this region is similar to that of several other countries with temperate or Mediterranean climates. The fauna is dominated by introduced Lumbricidae from Europe, in particular *Aporrectodea caliginosa*, *A. trapezoides* and *A. rosea*. Populations and species richness are usually low. The geographical distribution of the most common species is patchy. Earthworm abundance is correlated with a number of climatic and edaphic variables, most notably rainfall. The common species are active in the top 10 cm of the soil profile during winter-spring. Deep-burrowing (anecic) species are rare, in particular on mainland Australia.

Several studies have shown that earthworms can improve soil properties, help offset soil degradation (e.g. burial of lime to reduce soil acidity) and increase pasture production in southern Australia. Species differ in these abilities. The paucity of anecic species on mainland Australia may be partially addressed by introduction of the highly beneficial *A. longa* from Tasmania. Recent research has progressed means to mass-rear this species and predict where it might best establish.

Agricultural management practices can markedly influence earthworm numbers and biomass. Examples given here include tillage, drainage, irrigation, lime and fertiliser application, stocking rates and pesticide use.

Some authors have suggested the use of earthworms as biological indicators of the sustainability of agricultural practices. However, the patchy distribution of earthworms in space and time presents very significant hurdles for the successful adoption of such an approach.

Recommendations:

There are three major gaps in our current knowledge of the biology and role of earthworms in pastures in Australia:

1. In the south-eastern states, native earthworms (e.g. Megascolecidae), whilst rarer than the introduced Lumbricidae, can still constitute on average 40% of the fauna (and in many instance the majority). We know virtually nothing of the agricultural importance of this "resource".

2. Whilst a substantial amount is known about the biology of the exotic earthworms in southern pasture systems, ecological linkages between these to other soil biota (with the exception of root diseases), and indeed above ground pest and beneficial invertebrates (e.g. via nutrient flows), remain unstudied. If current aspirations towards establishing and harnessing improved functional biodiversity in our soils is to succeed, such linkages and the extent to which they are required need to be far better understood

3. Optimal use of water and key nutrients such as N and P, in particular the development of systems which optimise uptake by agricultural plants whilst minimising off-farm economic losses and environmental degradation through leaching and surface-run-off, are high priority topics across a wide range of agricultural industries, including those that are pasture-based. Previous studies elsewhere in the world have shown that earthworms, if managed properly, can contribute to substantial improvements in efficient usage of nutrients on-farm. We need to utilise earthworms as "soil engineers" – as taxa that can substantially create the soil architecture that determines water and nutrient movements through profiles and the abilities of plant roots to access these. We need to also realise, that like other macrofauna such as dung beetles, earthworms can be, and have been elsewhere, manipulated in agricultural landscapes. (**Recommendations F1, F2, G2).**

4.3.3 Dung beetles in Australian pastures (adapted from Appendix 6 by Dr. B. Doube)

The pollution of Australian pastures by the dung of cattle, sheep and goats, combined with the absence of an effective indigenous dung beetle fauna, has created an ecological imbalance which the introduction of exotic dung beetles to Australia has, in part, redressed over the past 30 years.

Dung beetles have specific climatic requirements and exotic species are now established in summer rainfall, even rainfall, and winter rainfall regions of Australia (Doube et al., 1991)**.** Dung beetles also show distinct preferences for different types of dung; there are beetles which prefer herbivore (cattle) pads or pellets (sheep, goats), and others which select omnivore and carnivore dung (Hanski and Camberfort, 1991). The current suite of introduced dung beetles comprises those that prefer cattle dung.

The intended benefits (Waterhouse, 1974) of introduced dung beetles were

- to reduce pasture spoilage,
- to bury the dung and so improve the fertility of soils and
- to control dung breeding flies and other pests

The establishment of exotic dung beetles in Australia has been highly successful, but most species have not yet reached their natural limit, and their dispersal to other regions should be promoted primarily through grazier organisations assisted by specialist advisers. A registry should be established to record deliberate dispersal of beetles in Australia. The dangers associated with the lack of dung beetle quarantine procedures within Australia need to be examined.

The highest research priority should be given to establishing the capacity of dung beetle species to reduce the organic and pathogenic pollution of water moving from pastures into water catchments. Interdisciplinary collaboration should be established with support from agencies responsible for water quality, pasture management and dung beetles.

Before additional research is directed towards mapping, cropping and redistributing established species, the agronomic benefits of dung beetles need to be established. The mechanisms responsible (eg, improved infiltration and storage of water, elevated soil organic status, deeper soil profiles) need to be documented so that the most beneficial species can be promoted.

Recommendations:

Research / extension:

1. Establish the capacity of dung beetle species to reduce pollution of water by pathogens and organic material (carbon and nutrients) that move from pastures into water catchments through surface water flow. (**Recommendations F1).**

2. The agronomic benefits of dung beetles need to be established - the mechanisms responsible (eg, improved infiltration and storage of water, elevated soil organic status, deeper soil profiles) need to be documented so that the most beneficial species can be promoted.

3. Determine the effect of anthelminthics on dung beetle activity, aiming to minimise collateral dung beetle mortality. (**Recommendation F2).**

4. Establish a registry of deliberate dispersal of beetles in Australia.

5. Examine the dangers associated with the lack of dung beetle quarantine procedures within Australia.

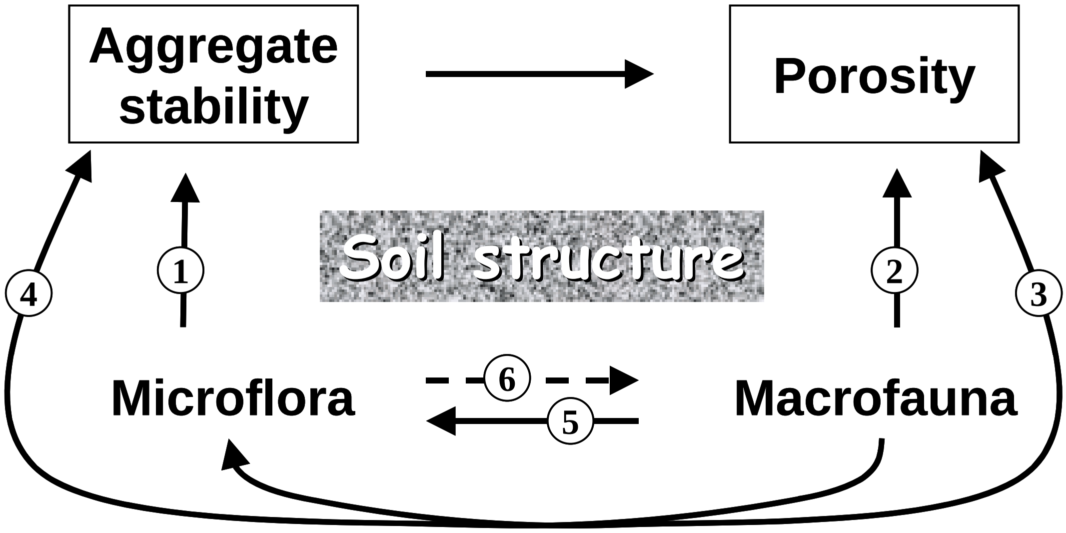

Figure 2

A conceptual model, developed based on available knowledge, linking different soil structural components with soil microfloral and macrofaunal activity. The relative importance of individual processes may differ between farming systems (i.e. cropping only compared to pasture-based, but the principles apply to both systems.

1. bacteria and fungi have a key role in the aggregate formation and stabilization;

2. macrofaunal activity affecting the pore structure e.g. formation of biopores, and distribution of plant and animal residues in the soil profile;

3. microfloral activity influencing the stability of pore walls;

4. macrofauna such as earthworms and their casts are known to influence aggregate formation;

5. macrofaunal influence on the composition of microfloral communities at microsites such as crop residues and rhizosphere and animal residues;

6. microfloral populations may influence the activity of macrofauna since bacteria and fungi serve as their food source.

4.3.4 Soil-borne diseases and their control

Murray and Davis (1996) reviewed the research on pasture plant diseases. They noted that there are many reviews on the diseases of pasture legumes but few on the diseases of grasses (eg Johnstone et al., 1987). This reflects the relative amounts of research on legumes compared to grasses, which are under-researched. Based on current evidence, the important pathogens in terms of widespread occurrence and potential for damage to pasture plants are listed in Table 1.

It is clear that little attention has been paid to pasture grasses, except in crop rotations where the grasses may be an alternate host for pathogens that attack cereal crops (Murray & Davis, 1996; Waller & Sale, 2001). David Roget, CSIRO Land and Water (personal communication) reported that barley grass is generally considered as a major host to the fungus that causes take-al of cereals, however in long-term (5 y) experiments near pure barley grass pastures, the fungus was not detectable (based on visual observations and plant biomass data). Development of disease suppression against take-all disease in continuous wheat rotation treatments has been reported (Simon and Sivasithamparam, 1989).

Table 1 Pathogens of pasture plants and methods of disease control

Pasture Species	Pathogen	Reference	Control method	Reference
Sub clover *Trifolium subterraneum*	*Phytophthora clandestina*	Taylor et al. (1985); Barbetti & Sivasithamparam (1987); Barbetti (1989); Hochman et al. 1990); Dear et al. (1993); Burnett et al. (1994); Purwantara et al. (1998a)	Resistant cultivars Potassium phosphonate Fungicide (Metalaxyl), Better drainage	Purwantara et al. (1998a); Greenhalgh et al (1994); Hochman et al (1990); Burnett et al (1994); Millar (1995)
	Pythium spp	Stovold (1974); Barbetti & Sivasithamparam (1987); Barbetti (1989)		
	Rhizoctonia spp	Barbetti (1989); Barbetti & Sivasithamparam (1987)	Better drainage	Millar (1995)
	Aphanomyces euteiches	Burnett et al (1994); Barbetti & Sivasithamparam (1987)	Fungicide	Burnett et al (1994)
	Fusarium avenaceum	Barbetti (1989); Barbetti & Sivasithamparam (1987)	Crop rotation	Millar (1995)
	Meloidogyne spp	Murray & Davis (1996)		
	Disease complexes	Flett & Clarke (1996) Burnett et al (1994); Barbetti & Sivasithamparam (1987)		
Medic (*Medicago* spp)	*Ph. clandestina, Pythium irregulare, Rhizoctonia, Fusarium*	Barbetti (1989) Barbetti (1989); Harvey et al. (2001) Barbetti (1989) Barbetti (1989)	Resistant cultivars, fungicides, rotation	Barbetti (1989)
Lucerne (*Medicago sativa*)	*Rhizoctonia,* *Ph. megasperma,* *Fusarium,* *Pythium* spp, *Sclerotinia trifoliorum* *Rhizoctonia* *Stagonospora,* *Colletotrichum*	Clarke (1999) Clarke (1999) Clarke (1999) Clarke (1999); Denman et al. (1995) Millar (1995) Millar (1995) Clarke (1999) Clarke (1999)	None Resistant cultivars Grazing / soil management Fungicide on seed Rotation Grazing / soil management Resistant cultivars, management	Clarke (1999) Millar (1995); Clarke (1999) Millar (1995) Clarke (1999)
White clover (*Trifolium repens*)	*Sclerotinia trifoliorum* Deleterious bacteria Clover cyst nematode	Millar (1995) Brown et al. (1994) (NZ) Kempster et al. (2001, 2002)	Grazing management, rotation Bacterial, chemical inducers of plant resistance	Millar (1995) Kempster et al. (2001, 2002)
Perennial ryegrass (*Lolium perenne*)	Range of diseases *Pythium* *Fusarium,* Deleterious bacteria	See Waller & Sale (2001) Falloon (1985) (NZ) Falloon (1985) (NZ); Millar (1995) Brown et al. (1994) (NZ)	 captan	 Falloon (1985) (NZ)

Control measures are available for some diseases (Table 1). Controls include the use of resistant and tolerant cultivars, seed- or soil-applied fungicides and grazing and soil management. Because an individual target plant species can be only a small component of the pasture system (in particular in permanent and unsown pastures), fungicide treatments are less efficient. This especially so because of the presence of many plant species including self-generating weeds that may support the survival of pathogen inoculum. This is one of the reasons for the belief that for white clover and subterranean clovers the development of resistant varieties is the best option where possible.

The fungicides used to control disease include metalaxyl (Hochman et al., 1990), potassium phosphonate (Greenhalgh et al., 1994), metalaxyl (Burnett et al., 1994) and captan (Falloon, 1985). However, Murray & Davis (1996) remark that the use of pesticides (fungicides) to control soil-borne diseases in pastures is rare in Australia. This may be because graziers are often uncertain of the risks of loss of pasture establishment or production due to disease and are therefore unwilling to invest in fungicides as control measures. This situation could change if methods of detecting the levels of important pathogens in soil were developed in conjunction with ways to predict the amount of damage that particular pathogen levels could cause (analogous to the DNA-based root disease testing that is currently done by the SARDI -C-Qentec partnership.

There has been much detailed work on *Phytophthora clandestina* which causes root rot on sub-clover. This problem can cause substantial losses in pasture production (Barbetti, 1989; Purwantara et al., 1998a). The scientific work ranges from the isolation and first description of the pathogen (Taylor et al., 1985), through to detailed studies of to host-pathogen interactions (Purwantara et al., 1998a,b). The research on host-pathogen interactions is a basis for breeding of disease-resistant sub-clover.

Some authors (Flett and Clarke, 1996; Burnett et al., 1994; Barbetti & Sivasithamparam, 1987) have addressed the occurrence of disease complexes in the field, and interactions between nematodes and pathogenic fungi, which can lead to disease being more severe (Murray & Davis, 1996). Disease complexes are likely to occur frequently in the field, and will make both research and its application more complex and difficult. The work of Harvey et al. (2001) shows that host-mediated selection occurs, for example for different genotypes within pathogenic *Pythium* species, so that there is scope for using crop – pasture rotations in a more sophisticated way to control disease caused by pathogens which have a very wide host range.

It is generally true that plants which have a better nutritional status (both macro-and micro-nutrients) are likely to be more tolerant or resistant to disease (Hannam and Reuter, 1987; Thongbai et al., 1993; Wilhelm et al., 1990). The trend towards reduced or insufficient nutrient inputs (including micronutrients) into pastures may be causing pasture decline through a reduced ability to tolerate existing pathogen levels in soil. Knowledge of specific interactions between nutrition and disease could be used to lift pasture productivity, via improved nutritional inputs leading to disease tolerance. For example, zinc applications have reduced the severity of *Rhizoctonia* in cereal crops (Neate, 1994). This approach would have the added advantage that many nutrients can be applied as foliar sprays to existing pastures.

We note that many pathology studies have used only single isolates of pathogens to investigate effects on plant hosts. This should be avoided wherever possible, because of the wide variation that can occur within populations of soil-borne pathogens, both within and between locations (Denman et al., 1995; Harvey et al., 2001).

Inoculants could be used to control diseases especially where pastures are sown. Specific soil biota have been used for this purpose in controlling diseases of crops and horticultural plants.

Compatibility with *Rhizobium* inoculants will be necessary. Pasture plants generally have an extensive root system compared to annual crops and are known to exhibit a lot of root exudation (e.g. ryegrass). These characteristics provide good potential for an introduced organism to grow. However, current methods for effective introduction of inoculants in unsown grassy pastures are very limited. To be successful, potential inoculant organisms for pasture systems should also posses other characteristics such as; effective on a target plant but not harm other plants in a mixed pasture plant community; able to survive in the presence of diverse microflora with in a mixed plant species community; able to recover from predation by soil fauna and be effective. Suppression can occur via biota that already exist in the soil.

Suppression of soil borne diseases, which is at least partly mediated by overall microbial activity, could reduce the impact of diseases without having to reduce the pathogen load in soil. In cropping systems there is a clear link between disease suppression and soil organic matter and carbon cycling, however there is no factual evidence for disuse suppression in pasture systems. This is a possible way to control pasture diseases via management of the system to promote the activity of native beneficial soil organisms.

Recommendations:

Context:

1. We note that many pathology studies have used only single isolates of pathogens to investigate effects on plant hosts. This should be avoided wherever possible, because of the wide variation that can occur amongst populations of soil-borne pathogens, both within and between locations.

2. Current knowledge of the relative importance of pathogens in different regions needs to be taken into account when planning research, because disease threats vary between agro-ecological regions. Note that for some high priority pathogen threats, management by rotation may be possible in pasture-cropping systems.

3. Since there is increased emphasis on grass species in pastures, there should be research effort towards pathology of these plants, including nematology.

4. Diagnostic probes for pathogens; this type of approach has been used successfully for cereal diseases but must be linked to information on interactions between disease and environment, to enable interpretation and generation of management options. If the pathogen level can be linked to a risk of damage due to disease (based on ecological knowledge) this will inform farmers about appropriate use of rotations and treatments such as fungicides.

Research:

1. Quantify losses due to disease using soil fumigation trials in areas where level of productivity loss is not known (**Recommendations A1, A2**).

2. Determine whether there are disease constraints to productivity of **grasses including native grasses** and, according to need, investigate options for their management . (**Recommendation E1).**

3. Investigate the **ecology and epidemiology** of **diseases** of **lucerne,** specific to agro-ecological zones.

4. Development of diagnostic DNA probes for the most important pathogens (fungi, nematodes). Link to 2 and 3. (**Recommendation E3).**

5. **Development and deployment of disease control measures, including** chemical and biological treatments, **for major pathogens**. Note: See also section 3.5 for recommendation on the use of biological and chemical inducers of plant resistance to nematodes and insects. (**Recommendation E2).**\

6. Investigate the potential for development of disease suppression in pasture soils (i.e. control of disease by soil biological and/or physical factors while pathogen is present). We recommend testing the concept first in pasture- crop rotations where D. Roget et al. (CSIRO) have already demonstrated suppression of crop diseases. (**Recommendation E4)**

7. Determine, for major pathogens, whether specific interactions between nutrition and disease could be used to lift pasture productivity, via improved nutritional inputs leading to disease tolerance. For example, zinc applications have reduced the severity of *Rhizoctonia* in cereal crops (Neate, 1994). Many nutrients can be applied as foliar sprays to existing pastures.

4.3.5 Plant Growth-Promoting Rhizobacteria ("PGPR") and other growth–promoting organisms

Inoculants are very commonly used in pasture systems in southern Australia, but this is almost exclusively restricted to inoculation of legume seed with *Rhizobium* and closely related genera of symbiotic nitrogen-fixing organisms. There will be a need for new research on symbiotic N fixing organisms to accompany trends in the introduction and use of pasture legumes (e.g. the more widespread use and breeding of lucerne, Humphries and Auricht, 2001). New legume-*Rhizobium* research should incorporate the most recent concepts on plant-microbe interactions.

However, we have excluded a full discussion of *Rhizobium* research from this review, because the topic has been very well reviewed recently (Date, 2001; O'Hara, 2001; Slattery et al., 2001; Thies et al., 2001; Sessitsch et al., 2002), and is the subject of regular national meetings (e.g. 13th Australian Nitrogen Fixation Conference, September 2002) and ongoing research around the country.

Other, new possibilities for inoculants in pasture systems are soil or rhizosphere organisms that promote seedling emergence (in sown pastures), stimulate seedling growth and/or re-growth following grazing, or that control insect pests and soil-borne diseases.

There are recent examples that could be considered for further research leading to commercial inoculant production and use in grazing systems and these concepts could be extended and used with other pasture plants. These are (a) soil bacteria for control of clover cyst nematode *Heterodera trifolii* (Kempster et al., 2001) and (b) microbial inoculants for temperate perennial pasture grasses (P. Mele et al., DNRE Rutherglen, unpublished, current study funded by Land and Water Australia). What makes the former example attractive for further research is evidence that the inoculant bacteria can induce systemic plant resistance to other pests such as the foliar pest blue-green aphid (Kempster et al., 2002). Chemical inducers of plant resistance ("BTH", Novartis) were also effective.

For seed-applied treatments, the aim must be to find a suitable method that is effective on the target plant with minimal non-target effects. It must also able to survive in the presence of a diverse soil microflora and interacting with the rhizosphere biota of other plants in a mixed plant species community.

The current technology for introduction of inoculants may restrict their use to sown pastures. However, the induction of systemic plant resistance by biological or chemical agents may allow the development foliar applications to control root diseases, which would be extremely useful in permanent pastures or in longer pasture-crop rotations.

Recommendations:

Context:

1. New legume-*Rhizobium* research should incorporate the most recent concepts on plant-microbe interactions.

2. Growth promotion treatments for pasture legumes need to be compatible with *Rhizobium* inoculation.

3. New treatments must aim to be effective on the target plant with minimal non-target effects.

4. The enormous field level variability in Australian soils demands a field-based approach rather than a controlled environment based approach.

Research:

1. Find effective symbiotic N fixing organisms to accompany trends in the introduction and use of pasture legumes (e.g. new lucerne introductions and breeding).

2. Further testing of bio-agents / chemical agents that induce systemic resistance to disease in pasture legumes. (Field-testing and assessment of potential for commercial development). Test the concept on grasses. (**Recommendation E2).**

3. Field-testing of emergence or growth-promoting organisms already selected for pasture grasses and assessment of commercial potential.

4. Development of management practices that enhance the native microbial communities that contain plant-specific beneficial microbes should also be investigated as an option (**Recommendation E4, and link to Section 4.3.4**).

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7 APPENDICES

7.1 APPENDIX 1. Examples of soil biological functions regulated by microbial activities.

Some examples of key microbial functions related to nutrient turnover in soil

Type of Microorganisms	Function in soil
Organisms that add nutrients to soil	
Nitrogen fixing microorganisms Symbiotic N_2-fixing bacteria (e.g. Rhizobium and Bradyrhizobium species)	Fix atmospheric nitrogen in symbiosis with legume plants
Non-symbiotic N_2-fixing bacteria (e.g. Azospirillum, Azotobacter species)	Fix atmospheric nitrogen in bulk soil, near crop residues and in rhizosphere
Organisms that transfer nutrients into plant available forms or facilitate their uptake by plants	
Nitrifying microorganisms (e.g. *Nitrosomonas* and *Nitrobacter* species)	Convert ammonia nitrogen into plant available nitrate form
Mycorrhizae (e.g. Vesicular Arbuscular Mycorrhizae, VAM) except for crops such as Canola, lupins etc.	Facilitate the uptake of phosphorus and zinc by most agricultural crops
Phosphorus solubilizing microorganisms (e.g. *Penicillium bilaii, P. radicum* and *Pseudomonas* sp, *Bacillus megaterium*)	Convert plant unavailable forms of P (organic or inorganic) into available forms
Sulphur oxidizing microorganisms (e.g. *Thiobacillus thioxidans* and most heterotrophic microorganisms)	Convert elemental sulphur and organic sulphur into plant available sulphates
Organisms whose action results in the loss of nutrients from soil	
Denitrifying microorganisms (e.g. *Thiobacillus denitrificans*)	Convert nitrate nitrogen into nitrogen and nitrous oxide gasses
Sulphur reducing bacteria (e.g. *Desulfovibrio* species)	Reduce sulphate sulphur into hydrogen sulphide gas
Organisms involved in the decomposition of crop residues	
Cellulolytic bacteria and fungi (e.g. *Cellulomonas* species, Basidiomycetes)	Decompose cellulose like compounds in crop residues

7.2 APPENDIX 2. Table of Nutrients in Microbial Biomass in Australian Agricultural Soils.

Microbial biomass carbon, nitrogen and phosphorus levels in the surface soils in different cropping regions of Australia.

Site location	Classification	Land use	pH	Clay (%)	Organic C (%)	Microbial Biomass C (ug C / g soil)	Total N (%)	Microbial Biomass N (ug N / g soil)	Microbial Biomass P (ug P / g soil)	Reference
Narayen, Qld.	Pelliv vertisol	Crop	7.8	58	2.8	675	0.3	213		Grace *et al*., 1992
Narayen, Qld.	Pelliv vertisol	Pasture	8.0	60	3.3	2700	0.3	408		Grace *et al*., 1992
Toowoomba, Qld.	Vertisol		8.6	73	1.6	367	0.13	55		Amato and Ladd, 1992
Harden, N.S.W.	Alfisol		6.3	14.5	1122 gm-2	80.7 (g C m-2)	112 gm-2	13.1 (g N m-2)		Gupta et al., 1994
Wagga East, N.S.W.	Alfisol		6.2	7	2.1	130	0.16	19		Amato and Ladd, 1992
Wagga Wagga, N.S.W.	Alfisol		6	15	1.5	120	0.12	18		Amato and Ladd, 1992
Caliph, S.A.	Entisol		8.2	5	0.7	54	0.06	8		Amato and Ladd, 1992
Caliph, S.A.	Alfisol		8.6	20	1.0	169	0.13	25		Amato and Ladd, 1992
Freeling, S.A.	Vertisol		8.4	42	1.8	317	0.20	47		Amato and Ladd, 1992
Kapunda, S.A.	Alfisol		6.4	13	1.6	111	0.17	17		Amato and Ladd, 1992
Mallala, S.A.	Calcixerollic xerochrept	Crop	8.3	21	1.5		0.17		22	McLaughlin and Alston, 1986 McLaughlin *et al*., 1988
Northfield, S.A.	Vertisol		8.3	43	1.7	302	0.12	45		Amato and Ladd, 1992
Paskeville, S.A.	Mollisol		8.3	35	2.5	479	0.28	71		Amato and Ladd, 1992
Roseworthy, S.A.	Alfisol		8.4	8	1.1	186	0.09	28		Amato and Ladd, 1992
Tarlee, S.A.	Alfisol		6.3	17	1.5	102	0.16	15		Amato and Ladd, 1992
Tarlee, S.A.	Alfisol		6.2	27	2.5	211	0.24	31		Amato and Ladd, 1992
Urrbrae, S.A.	Alfisol		6.2	13	1.4	91	0.08	14		Amato and Ladd, 1992
Waikerie, S.A.	Calcic Xerosol	Crop	8.3	3	0.6-1.0	200-400	-	20-40		Gupta and Roget, unpubl.
Glenloth, Vic.	Alfisol		6.7	25	1.4	149	0.10	22		Amato and Ladd, 1992
Horsham, Vic.	Vertisol		8.3	46	1.2	228	0.11	34		Amato and Ladd, 1992
Rutherglen, Vic.	Calcic luvisol	Crop	6.5	22	1.2	246	0.13	33		Carter and Mele, 1992
Walpeup, Vic.	Alfisol		7.3	2	0.4	36	0.02	5		Amato and Ladd, 1992
Merredin, W.A.	Alfisol		6.4	18	1.0	69	0.08	10		Amato and Ladd, 1992
Tammin, W.A.	Xanthic hapludox	Pasture	5.7	NA	0.8	176	0.06	40		Sparling *et al*., 1994
Wongan Hills, W.A.	Entisol		6.3	7	1.0	45	0.07	7		Amato and Ladd, 1992
Wongan Hills, W.A.	Alfisol	Crop	5.4	3.4	0.55	200	0.045	29		van Vliet *et l*.,unpublished
Wongan Hills, W.A.	Alfisol	Pasture	5.4	3.4	0.55	500	0.045	71		van Vliet *et al*., unpublished
Narayen, Qld.	Pelliv vertisol	Woodland	7.1	42	6.5	2700	0.6	575		Grace *et al*., 1992
Tammin, W.A	Xanthic hapludox	Woodland	5.4	NA	1.1	163	0.04	32		Sparling *et al*., 1994
Tammin, W.A	Xanthic hapludox	Reveg	5.7	NA	0.4	201	0.04	37		Sparling *et al*., 1994

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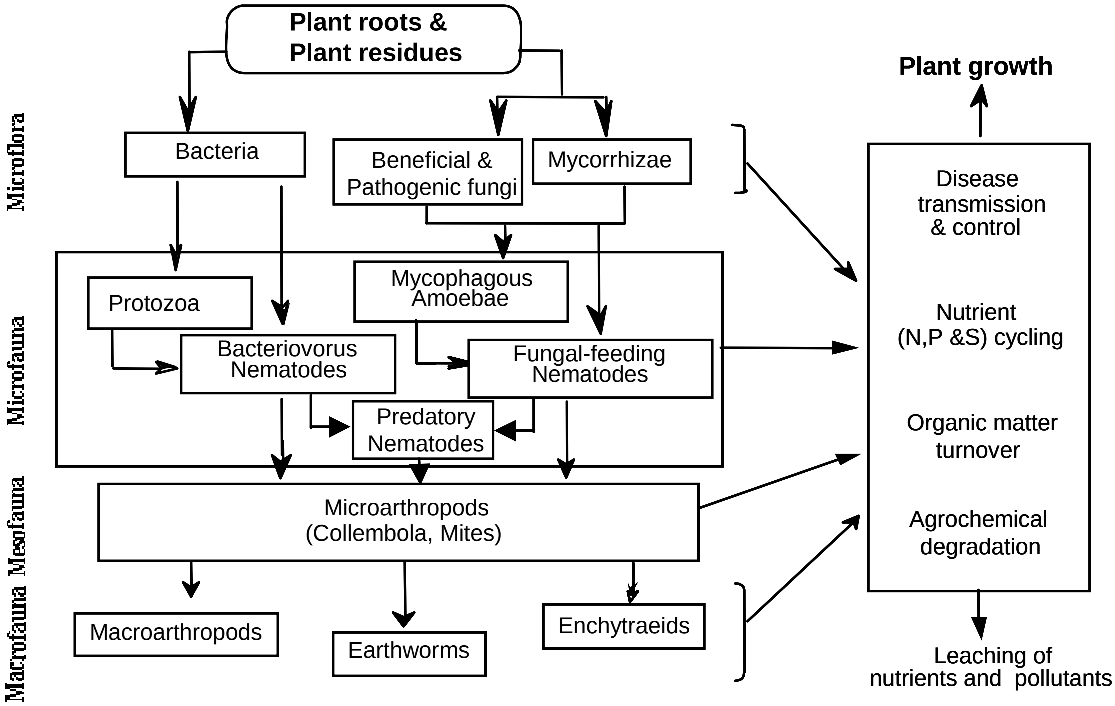
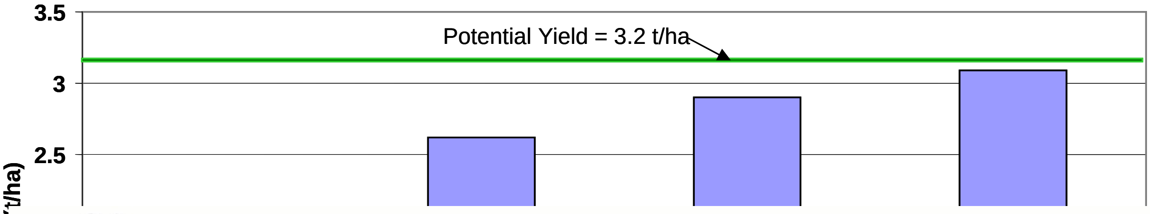
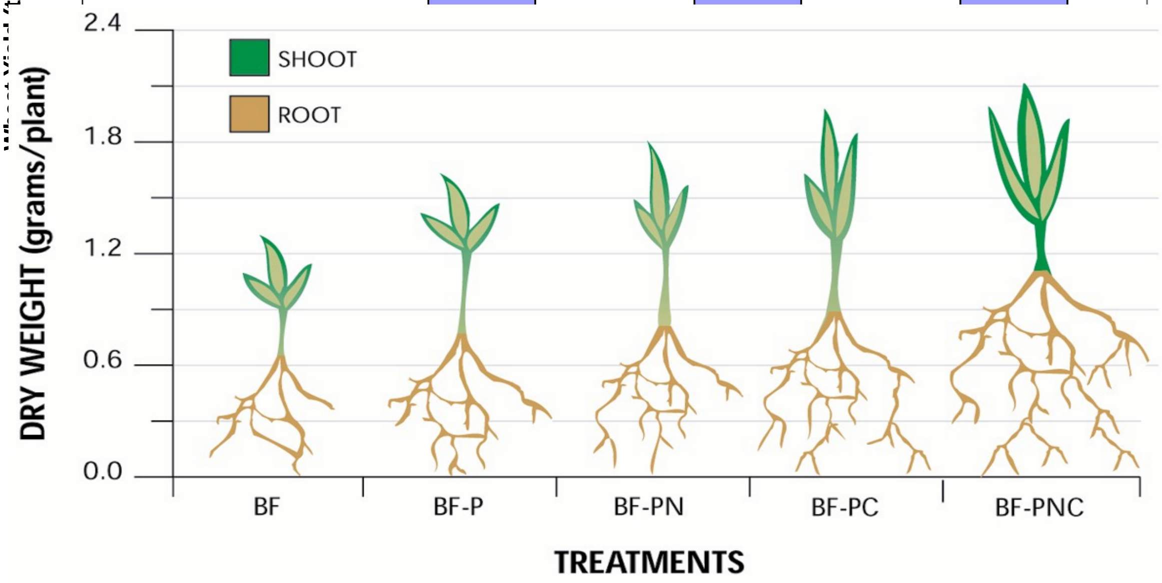
7.3 APPENDIX 3. Diagram of the Soil Detritus Food with Biological Functions.



Appendix 3. The different groups of soil biota are linked in a detritus food-web model in order to express their role in key soil biological processes. This model is based on published information (based on information from Hendrix et al., 1986; Beare et al., 1992; Roper and Gupta, 1995 and Gupta and Neate, 1999).

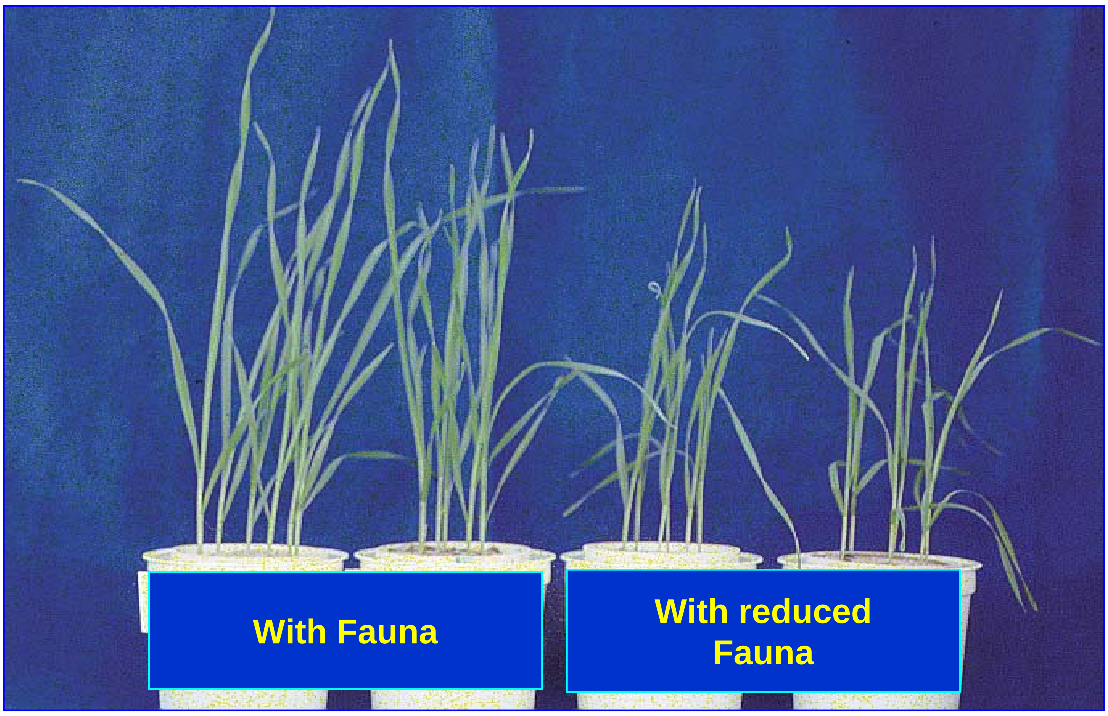
7.4 APPENDIX 4. Benefits of Soil Biological Activity for Plant Growth



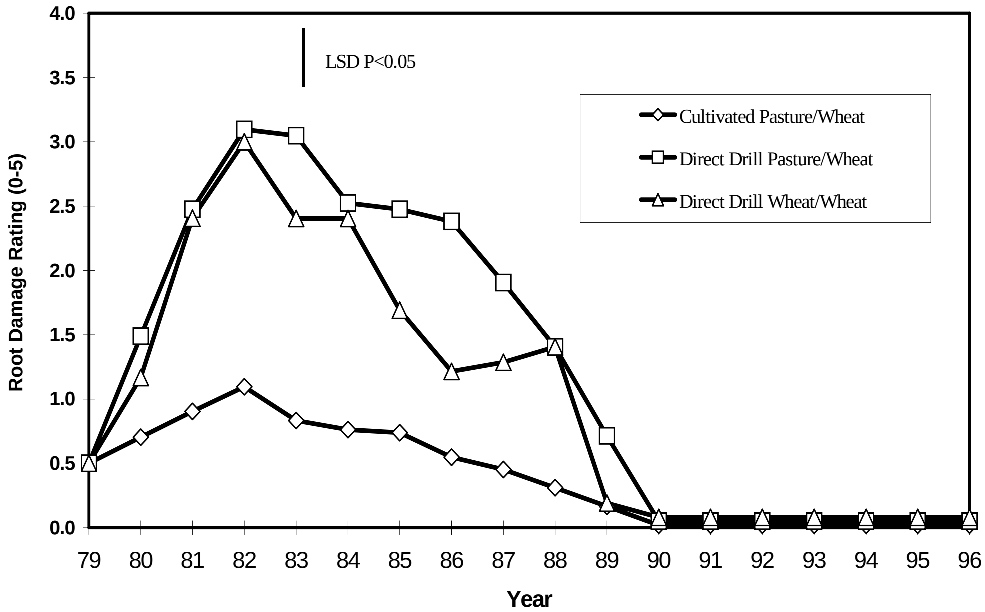


Appendix 4a. Components to yield improvement in wheat crops as determined by fumigation and crop rotation treatments in field experiments (David Roget, unpublished).

Appendix 4b. Effect of soil biota composition on the growth of wheat plants (above ground and below ground dry weights at five weeks after germination) in an inclusion pot experiment using a West Australian soil. B – bacteria;; F – fungi; P – protozoa; N – nematodes; C – collembola. Following the sterilization of soil to remove all soil biota individual groups of microflora and fauna were added prior to sowing (van Vliet P, Gupta V.V.S.R. and Abbott, L., 1998 as reported in Gupta et al., 1998).



Appendix 4c. Effect of soil biota composition on the growth of wheat plants (at five weeks after germination) in an exclusion intact core experiment using a south Australian soil. Intact soil cores (10 x 10 cm) of surface soil were collected from the long term farming system experiment showing disease suppression at Avon, SA and populations of mesofauna (collembola and mites) were reduced by >95%, before the sowing of wheat seeds, using a physical exclusion procedure (Gupta et al., 1999).



Appendix 4d. The development of disease suppression as indicated by the decline in the Rhizoctonia root rot of wheat at Avon, South Australia during 1979 to 1996 (adapted from Roget, 1995).

7.5 APPENDIX 5. Managing Earthworms as a Resource in Australian Pastures

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Summary

Earthworms are the most obvious element of the macrofauna in pasture soils in southern Australia. The earthworm fauna in pastures in this region is similar to that of several other countries with temperate or mediterranean climates. The fauna is dominated by introduced Lumbricidae from Europe, in particular *Aporrectodea caliginosa*, *A. trapezoides* and *A. rosea*. Population numbers and species richness are usually low. The geographic distributions of the most common species are patchy. Earthworm abundance is correlated with a number of climatic and edaphic variables, most notably rainfall. The common species are active in the top 10 cm of the soil profile during winter-spring. Deep-burrowing (anecic) species are rare, in particular on mainland Australia.

Several studies have shown that earthworms can improve soil properties, help offset soil degradation (e.g. burial of lime to reduce soil acidity) and increase pasture production in southern Australia. Species differ in these abilities. The paucity of anecic species on mainland Australia may be partially addressed by introduction of the highly beneficial *A. longa* from Tasmania. Recent research has progressed means to mass-rear this species and predict where it might best establish.

Agricultural management practices can markedly influence earthworm numbers and biomass. Examples given here include tillage, drainage, irrigation, lime and fertiliser application, stocking rates and pesticide use.

The use of earthworms as biological indicators of the sustainability of agricultural practices has been suggested by some authors. However, the patchy distributions of earthworms in space and time present very significant hurdles for the successful adoption of such an approach.

Four major gaps are obvious in our current knowledge of the biology and role of earthworms in pastures in Australia:

1. Hardly anything is known of the fauna in sub-tropical and tropical systems and its ability to influence soil properties and pasture production there.

2. In the south-eastern states, native earthworms (e.g. Megascolecidae), whilst rarer than the introduced Lumbricidae, can still constitute on average 40% of the fauna (and in many instance the majority). We know virtually nothing of the agricultural importance of this “resource”.

3. Whilst a substantial amount is known about the biology of the exotic earthworms in southern pasture systems, ecological linkages between these to other soil biota (with the exception of root diseases), and indeed above ground pest and beneficial invertebrates (e.g. via nutrient flows), remain unstudied. If current aspirations towards establishing and harnessing improved functional biodiversity in our soils are

to succeed, such linkages and the extent to which they are required need to be far better understood.

4. Optimal use of water and key nutrients such as N and P, in particular the development of systems which optimise uptake by agricultural plants whilst minimising off-farm economic losses and environmental degradation through leaching and surface-run-off, are high priority topics across a wide range of agricultural industries, including those that are pasture-based. Previous studies elsewhere in the world have shown that earthworms, if managed properly, can contribute to substantial improvements in efficient usage of nutrients on-farm. We need to utilise earthworms as "soil engineers" – as taxa that can substantially create the soil architecture that determines water and nutrient movements through profiles and the abilities of plant roots to access these. We need to also realise, that like other macrofauna such as dung beetles, earthworms can be, and have been elsewhere, manipulated in agricultural landscapes.

There is very limited scientific input in soil zoology in Australia at present. Whilst there was a "flush" of earthworm researchers in southern Australia in the early 1990's, there is currently none fully active in this field at present. G. Baker (CSIRO Entomology, Canberra) and Y. Chan (NSW Agric., Wagga Wagga) have retained some on-going research with earthworms in pastures (principally through NSW Agric.'s "Acid Soil Action" program).

1. Introduction

Earthworms are well known for their abilities to improve soil structure, fertility and agricultural production (Lee 1985; Edwards & Bohlen 1996). For example, research in New Zealand has shown that introduction of earthworms to pastures lacking them can enhance pasture production by 25% in the long term (Stockdill 1982). This improvement in pasture production in New Zealand resulted especially from the introduced earthworms feeding upon a thick layer of dead organic matter that had accumulated at the soil surface. The breakdown of the organic mat returned nutrients to the soil and enhanced water infiltration. Comparable research in northern Tasmania (Temple-Smith 1991) and on-farm applications (D. Ford, "Woolnorth" & B. Farquar, "Rushy Lagoon"; pers. comm.) have also demonstrated similar increases in pasture production can be achieved using the same technologies as used in N.Z. (inoculating pastures by spreading sods of soil containing earthworms). In addition, significant increases in plant production have resulted from introductions of earthworms in several other countries (e.g. Ireland, Netherlands, U.S.A.) (see Baker 1998a for references).

Agricultural soils in southern, mainland Australia are generally poor in structure and fertility. The work cited above stimulated a flurry of research in the late 1980's – early 1990's aimed at improving the management of earthworms as a resource in agricultural soils in south-eastern Australia (Temple-Smith & Pinkard 1996). Several factors further encouraged this expansion in earthworm research. Increased on-farm costs (fuel, labour, machinery), reduced values in agricultural products, and a greater awareness of soil structural decline encouraged farmers to adopt reduced cultivation techniques. Under such practices, the abundance of earthworms is enhanced (Rovira et al. 1987), and their presence in optimal numbers is needed to replace some of the benefits previously brought by the plough. In addition, the increasing costs of fertilisers, as well as the pollution problems they bring (e.g. through leaching and erosion into waterways), stimulated more thought on more efficient and safer means of transfer of nutrients to plants. Studies in other countries, which had shown the potential for earthworms to help offset soil degradation (e.g. improved lime burial and reduction of soil acidity, improved water infiltration and rates of breakdown of surface litter leading to reduced surface run-off of phosphorus and nitrogen) (Sharpley et al 1979; Springett 1983) also heightened interest in introducing such benefits to Australia.

During the late 1980's and through the 1990's research on earthworms in southern Australia was aimed primarily at determining the distribution and abundance of the earthworm fauna in agricultural soils, measuring the effects of the most common species on soil properties and plant production, and recognising means by which the beneficial role of earthworms can be enhanced (e.g. optimal farm management practices, introduction of new taxa) (Baker 1998a). This overview briefly considers progress that was made on these topics and gaps in our knowledge that remain that could, if filled, lead to benefits for grazing industries. The focus here is on pastures. There is also a substantial literature available on earthworms in grain cropping systems in southern Australia. Such information is only referred to here where it is of particular relevance. The vast majority of earthworm research that has been conducted in Australia, has been in southern temperate and mediterranean climate regions. The biology, role and management of earthworms in tropical grazing systems in Australia is more or less uncharted territory. Parallels may be sought in the extensive studies of P. Lavelle and colleagues in Africa and Central and South America (see Lavelle et al 1999 for an introduction to this literature).

2. The Earthworm Fauna

Extensive surveys have demonstrated that the densities and species richness of earthworms are generally low in soils used for pastures in southern Australia (Kingston & Temple-Smith 1989; Mele 1991; Baker et al 1992; Garnsey 1994a; Lobry de Bruyn & Kingston 1997; Baker 1998a; Mele & Carter 1999a; Baker et al 2003a). The earthworm fauna is dominated by exotic species, most notably Lumbricidae (e.g. *Aporrectodea caliginosa*, *A. trapezoides*, *A. rosea*), which have been accidentally introduced from Europe. Dominant species vary regionally and between habitat types. For example, *A. trapezoides* is dominant in permanent pastures in S.A. and southern N.S.W., but *A. caliginosa* is more abundant in similar pastures in western Vic. In pasture-cereal rotations in the same regions, *A. rosea* is the dominant species. Native species (Megascolecidae), which are common in undisturbed, native habitats, are generally rarer in agricultural soils than exotics. Reasons for this relative rarity of native species are poorly understood, but tillage and changes in shelter, food type and soil fertility have been suggested as possibly important. Interestingly, native species are more common in pasture soils in Victoria and southern N.S.W. (e.g. 42% here are native) than they are in S.A. and W.A. Reasons for this cline in abundance are not clear, but possibly it reflects differences in summer aridity.

Having said that exotic species tend to dominate earthworm communities in pastures in southern Australia, many pastures nonetheless lack exotic species. It may be that these absences of exotic species simply reflect lack of opportunity to colonise thus far, rather than unsuitable habitat. Environmental factors which determine the geographic distribution and abundance of the earthworm fauna are poorly understood. Many auto-correlated variables (climatic, edaphic, land-use) are weakly related to earthworm abundance, with rainfall and soil particle size somewhat understandably most commonly explaining the greatest variances (Baker 1998a).

The common earthworm species in agricultural soils in southern Australia are endogeic, feeding predominantly on decomposing organic matter that is already incorporated into the mineral soil layer. These worms are active in the top 10 cm of soil for about 4-5 months of the year (early winter to early spring), when soils are moistest (Baker et al 1992, 1993c,d; Garnsey 1994a). During the summer months, most worms are inactive deep in the soil. There are very few anecic species in the fauna (i.e. species that feed at the soil surface and burrow deeply during the active season). Such species have the potential to markedly influence soil properties at depth (e.g. porosity), thus encouraging deeper penetration of water, nutrients and rooting of plants. In contrast to this paucity of anecic species in pasture soils in southern Australia, earthworm communities in similar habitats in other parts of the world are commonly dominated by anecic species (e.g. 70% of the earthworm biomass) (Lavelle 1983). One anecic species, *A. longa*, is common in pastures in northern Tasmania (Baker 1998a) (see further comment on the potential in extending the distribution of this species below). Epigeic earthworms, those that live near the soil surface and feed on recently produced dead organic matter, are patchy in distribution and abundance in southern Australia. *Lumbricus rubellus* can be very abundant where conditions are moist. *Microscolex dubius* is more widespread, but rarely abundant. It survives summer as resistant cocoons (i.e. eggs) in the dry, surface soil (Doube & Auhl 1998).

3. Effects of Earthworms on Soil Properties and Plant Production

There is a great variety of ways in which earthworms can influence soil properties and plant production (Lee, 1985; Lavelle, 1988; Curry, 1994). Several studies have been made of the influence of the most common earthworm species in agricultural soils in southern Australia on soil structure (e.g. Barley, 1959c; Doube et al., 1994b,c; Hindell et al. 1994a,b,c, 1997; Hirth et al., 1994, 1996; Curry & Baker, 1998), nutrient availability (Barley & Jennings, 1959), burial of surface organic matter and lime (Barley, 1959b; Baker et al., 1993e, 1995), distribution of beneficial microorganisms (Stephens & Davoren, 1994; Stephens et al ., 1993b, 1994a,b; Doube et al., 1994a,d), reduction of root diseases (Stephens et al., 1993a, 1995; Stephens & Davoren, 1997), and plant yield and quality (Abbott & Parker, 1981; Temple-Smith et al., 1993; Garnsey, 1994b; Stephens et al., 1994; Baker et al., 1997b). Two of these topics will be addressed in more detail: the influence of earthworms on pasture production and the burial of surface-applied lime and organic matter.

Laboratory and field trials have shown that some exotic earthworm species (mostly Lumbricidae) can substantially improve the availability of soil nutrients and the quality and quantity of pasture and crop production in Australia. For example, Baker (1998a) demonstrated that the anecic earthworm, *A. longa* could increase pasture yield by 60% within field cages at one site in the Mt Lofty Ranges, S.A. within 5 months. Similar trials throughout S.A., Vic and southern N.S.W. have also demonstrated that the endogeic species, *A. caliginosa* and *A. trapezoides*, as well as *A. longa*, can increase pasture production substantially (Baker 1997; Baker et al 1996, 1999b, 2002b; Chan et al in prep.). The degree of increase is dependent upon earthworm density. A few studies have shown that induced increases in pasture production are additive across earthworm species (Baker 1998b) – i.e. that species (functional) diversity within earthworm communities matters. But much more work to fully substantiate this finding is warranted.

The influence of native earthworms (Megascolecidae) on pasture production has been relatively poorly studied. In the main, native species have failed to influence plant growth (Baker et al 1996; Baker 1998a), but in one study (Baker et al 2003a) *Spenceriella macleayi* did slightly increase ryegrass growth in a glasshouse experiment.

The majority of research on earthworm effects on pasture production in Australia has either not discriminated between pasture species or focussed on ryegrass. Research on grain crops in Australia (e.g. Baker et al 2003b) and overseas (Brown et al 1999) has demonstrated that earthworm effects vary between plant types. In the main, legumes are less responsive than cereals. The abilities of legumes to fix their own nitrogen may obviate the “need” for earthworms in some circumstances. Some studies have demonstrated how plant growth responses to earthworms vary between sites and soil types, ranging from mostly positive, through neutral, to the occasional negative response (Doube et al 1997; Baker et al 1999b). Reasons for this variability are not at all clear.

Most, if not all, studies of the abilities of earthworms to enhance nutrient transfer from fertilisers and organic residues to agricultural plants in Australia have been confined to grain crops (G. Baker, unpub. data; Baker & Amato 2001; Baker et al 2003b). Some studies have explored the influences of earthworms on pasture root growth (Hirth et al 1997, 1998), with some similar studies being made in New Zealand (e.g. Springett & Gray 1997).

As in many other countries, soil acidity is a major environmental problem in high rainfall regions of Australia (Coventry 1985; Chartres et al 1992). The use of ammonium-based nitrogen fertilisers and nitrogen fixing legumes has contributed significantly to soil acidification. Lime is applied to the surface of the soil to offset acidity but is generally slow to be incorporated into the root zone where it is needed (Helyar 1991). It is often too costly or inappropriate to incorporate lime mechanically using tillage (e.g. in permanent pastures on steep slopes). Research in New Zealand (Stockdill & Cossens 1966; Springett 1983, 1985) has shown that some species of earthworms have the potential to bury lime and increase soil pH. Similar experiments have recently been conducted in south-eastern and south-western Australia to determine the species most likely to be useful in reducing soil acidity in this way (Baker 1998a; Baker et al 1993e, 1998, 1999c; Chan et al in prep). The results suggest that the endogeic species *A. trapezoides* and *A. caliginosa* can be effective in burying surface-applied lime into the top few cm of soil, but the anecic species, *A. longa*, is much more effective in burying it deeper into the profile (e.g. to 15 cm within a few months). Some other species (e.g. *A. rosea*) are ineffective. Baker et al (1993e, 1999c) explained the differences between species in terms of their relative surface activities and depth of burrows. *A. longa* greatly disturbs the soil surface during its feeding and creates surface venting pores down which lime particles can be washed by rainwater. Similar transport of other surface-applied materials (gypsum, fertilisers) is to be assumed but has not been tested.

Large amounts of cattle and sheep dung accumulate on the surface of Australian pastures (Waterhouse 1974). As well as fouling pasture growth and increasing fly numbers, this dung represents an inefficient return of plant nutrients to the soil. Many species of exotic dung beetles have been introduced to Australia to encourage the burial of cattle dung (Tyndale-Biscoe 1990), but the role of earthworms in this process has largely been ignored (Ferrar 1975). Holter (1979) showed that *A. longa*, working in concert with dung beetles, was particularly effective in burying cattle dung in a Danish pasture, and Martin and Charles (1979) demonstrated that *A. caliginosa* and *L. rubellus* buried large amounts of both cattle and sheep dung in New Zealand pastures. The influence of earthworms on the burial of sheep dung has been measured in southern Australia on a few occasions, in cage experiments (Baker 1998a). *A. longa* is clearly very efficient at burying such dung, more so than several other species, especially some natives. The influence of earthworms on cattle dung burial and on any dung type at field scale in Australian pastures remains unstudied.

Optimal use of key nutrients is central to sustainable agricultural production and catchment health. In particular, the development of systems which maximise the uptake of applied fertiliser by plants and the recycling of nutrients from plant residues, whilst minimising off-site economic losses and non-target impact through leaching and surface run-off is viewed by farmers and the broader community as a high priority. Research in New Zealand (Sharpley et al 1979) has shown that earthworms can rapidly bury surface organic matter in pastures and reduce N and P loss (leached out of the dead organic matter) from sloped agricultural fields (by factors of 4 to 8 X). Similar research to that in NZ has not been done in Australia, but it seems likely that similar benefits may accrue through retention of nutrients on farm if earthworm communities were managed well. Certainly, opportunities exist where ± earthworm treatments could be imposed on surface-runoff trials that are currently being conducted in Australian pastures to test for impacts.

4. Effects of Agricultural Management Practices on Earthworms

It is well known world-wide that agricultural management practices such as drainage, irrigation, lime, fertiliser and slurry application, pesticide use, stocking rate, tillage, crop rotation and stubble retention can influence earthworm numbers and biomass (Lee 1985; Lavelle et al 1989; Curry 1994; Fraser 1994; Edwards & Bohlen 1996).
Rovira et al (1987) demonstrated that the abundance of earthworms in a red-brown earth soil in S.A. was doubled by direct drilling of cereals, in contrast with conventional cultivation. Fewer earthworms were found under a lupin-wheat rotation than under a pasture-wheat rotation. Haines & Uren (1990), Buckerfield (1993a, 1994), Buckerfield & Wiseman (1997) and Mele & Carter (1999b) have provided further evidence that tillage reduces earthworm numbers in Australia and that pastures in rotation with cereals and retention of stubbles can increase abundance. Tillage can reduce earthworm numbers in a variety of ways. Earthworms may be damaged directly by machinery, exposed to predation or adverse weather, their burrow systems may be disrupted, or the availability of suitable food may be reduced (Edwards & Lofty 1982a; Springett 1983; Lee 1985).

Water-logging of soils is a significant problem in high rainfall zones of south-eastern Australia (Reed & Cocks 1982). Underground drainage is expensive to install, but can significantly increase lucerne production (Chin 1990). Drainage can significantly increase earthworm numbers (Baker 1998a). Such increases in earthworm numbers may contribute, at least in part, to the observed increases in plant production under drainage.

Without irrigation, pasture growth usually ceases during the hot, dry summer in southern Australia and no earthworms are active in the root zone (Baker et al 1992, 1993c,d). Baker et al (1993c) suggested that earthworm activity ceases in soils above approximately 150kPa water suction potential. With irrigation, several species remain active during summer (e.g. *A. trapezoides*, *A. caliginosa*, *A. rosea*). Irrigated pastures in the Mt Lofty Ranges of S.A. are dominated by *A. caliginosa* in winter whereas dryland pastures are dominated by *A. trapezoides*. This difference reflects *A. caliginosa*'s greater dependence on moist soil (and its more northerly distribution in the pair's European distribution). *L. rubellus* occurs in small numbers in irrigated pastures in S.A., but has never been found in dryland fields. In eastern Australia, where soil moisture levels can be higher, *L. rubellus* is occasionally very abundant. Lobry de Bruyn & Kingston (1997) also demonstrated shifts in earthworm community structure resulted from irrigation in northern Tas.

Noble & Mills (1974) reported that the numbers of *A. caliginosa* increase with irrigation in pastures, but decline over time under heavy irrigation. They explained this population decline as due to increased surface activity and greater predation by birds. In Tasmania, Kingston (1989) and Lobry de Bruyn (1993) recorded decreases in the abundance of *A. caliginosa* with irrigation, but increases in numbers of *L. rubellus*. The authors explained their results in terms of trampling-induced mortality for both species (see below) and increased parasitism by Diptera, overcome for *L. rubellus* by greatly enhanced summer survival and reproduction.

Whilst earthworms avoid freshly limed soil (Doube et al 1995), several authors (see Edwards & Lofty 1977) have shown that liming an acid soil can increase earthworm abundance in the longer term. Springett & Syers (1984) argued that the change in pH per se influences earthworms, rather than the availability of calcium. Edwards & Lofty (1977) concluded that population responses to lime are not likely to occur if the initial pH of the soil is > 4.5-5, above which most species are insensitive. Mixed results have been recorded in response to liming pastures in south-eastern Australia. Baker (1992) found that liming a pasture on a clay loam soil in western Victoria had no overall impact on total earthworm numbers nine years later (rates of 0-10 t ha^{-1}, pH range 4.5-5.6 at the time of earthworm sampling), but at the species level there were increases in abundance with increased pH (*Octolasion cyaneum* and *M. dubius*), decreases (*Heteroporodrilus* sp. and *Spenceriella* sp.) and no significant changes (*A. trapezoides* and *A. rosea*). In contrast, Buckerfield (1994) reported that liming a pasture in S.A. and increasing soil pH over a similar range to that of Baker (1992) increased the abundance of *A. trapezoides*. In field cages in S.A. and Vic., the addition of 4 t lime ha^{-1} had no influence on the establishment of *A. longa* after five months, in a range of soil types (initial pH 4.3-5.2), but reduced the survival of *Spenceriella* sp. at some sites (Baker et al 1999a; Baker unpubl. data). Garnsey (1994) reported that the addition of lime (5 t ha^{-1}) increased the abundance *of A. trapezoides*, *L. rubellus* and *A. longa* in one Tas. pasture after one or two years (initial pH = 5.9), but had no influence in another (initial pH = 6.0). Garnsey attributed the earthworm response he did get to an indirect effect mediated through increased clover production and hence improved food quality for the worms. In other studies at several lime trial sites in pastures in southern N.S.W., Baker et al (unpub. data) failed to detect responses in the abundance and biomass of earthworms (Megascolecidae & Lumbricidae) to liming. The numerical responses of earthworms to liming seem likely to vary according to the soil type, earthworm species present, and the range of pH involved.

Barley (1959a) showed that the numbers and weights of earthworms (probably mostly *A. rosea* and *A. trapezoides*) increased with the addition of superphosphate to a pasture in S.A. Barley argued this was due to an increase in plant production and hence available food (as decomposing plant material). Similarly, Fraser et al (1994) found that earthworm numbers (mostly *A. caliginosa* and *L. rubellus*) increased with superphosphate use and plant production in a New Zealand pasture. However, such associations are not always evident. Baker et al (1993a,b, 1998) were unable to demonstrate changes in earthworm densities following superphosphate applications to pastures in Vic. and S.A. Food supply was possibly not limiting for earthworms in these latter situations. Lee (1985) indicated that some fertilisers can acidify soils and hence reduce earthworm abundance. The additions of nitrogenous fertilisers and moderate amounts of manures and slurries increase earthworm numbers (Gerard and Hay 1979; Edwards & Lofty 1982b; Curry 1994). However, excessive amounts of the latter may reduce abundance.

Disposal of human sewage sludge by environmentally acceptable means poses a challenge world-wide. However, safe and profitable disposal of such sludge, as biosolids, has been achieved in Europe and North America through its addition to pastures (Smith 1996). The disposal of biosolids has also been considered in N.S.W. (Joshua et al 1998). An experiment which commenced near Goulburn in 1992 to assess the benefits and risks associated with the application of dewatered biosolids (DWB) to pastures grazed by sheep was surveyed 7 years later to measure impacts on the abundance and diversity of earthworms (Baker et al 2002b). Application of DWB increased local earthworm abundance. Species composition varied with amount of DWB applied. Introductions of earthworms (*A. longa* and *A. caliginosa*), which were not present naturally at the site, were successful (in the short term) and unaffected by DWB.

Water-repellency of sandy soils is a serious agricultural problem across southern Australia, leading to significant land degradation and losses in production (Bond 1969). One potential way of offsetting the effects of these non-wetting sands is to add dispersible clay to assist with water infiltration and holding capacity (Ma'shum et al 1989). A field trial in the southeast of S.A. (Baker et al 1998), in which varying amounts of clay had been added to a non-wetting sandy soil beneath a pasture, demonstrated that the abundance and biomass of *A. trapezoides* increased with the addition of clay.

Trampling by agricultural animal stock is likely to squash earthworms that live near the soil surface, compact the soil, and return organic matter and nutrients in a different form (dung and urine) and spatial distribution than occurs with senescent plants. Stock therefore can influence earthworm populations. However there has been surprisingly little data published on the interactions between stocking rates and earthworm abundance. Lobry de Bruyn (1993) excluded dairy cattle from pastures in Tas. and demonstrated that trampling reduced the abundance of both *A. caliginosa* (19%) and *L. rubellus* (25%). As well as the difference due to trampling per se, pasture growth was reduced in the untrampled plots and species composition also changed (more weeds). The mechanism driving the change in earthworm populations was therefore not clear. Nevertheless, both Kingston (1989) and Lobry de Bruyn (1993) have suggested that mortality of *A. caliginosa* and *L. rubellus* in irrigated dairy pastures in Tas. is due, at least in part, to direct trampling effects, exacerbated by greater surface activity in moist soils, and to compaction of the soil which renders it unsuitable for eathworm survival.

With smaller animal stock, Hutchinson & King (1980) observed that earthworm populations were highest at a stocking rate of 29 sheep ha^{-1} in pastures in northern N.S.W. This stocking rate corresponded with maximum primary productivity. On the other hand, Baker et al (1993a,b, unpub. data) could show no consistent pattern between earthworm abundance and the stocking rate of sheep (range 5-23ha^{-1}) in several pastures in western Vic., N.S.W. and S.A.

Pizl (1992), Sochtig & Larink (1992) and Hansen & Engelstad (1999) have demonstrated significant declines in earthworm numbers following compaction from machinery traffic in orchards, cereal fields and dairy pastures in the Czech Republic, Germany and Norway respectively. The only comparable Australian study is that of T. Ellis in S.A. (pers. comm.), who demonstrated a reduction of earthworm numbers beneath wheel tracks in a controlled-traffic, cereal production trial.

Lee (1985), Edwards & Bohlen (1992, 1996) and Curry (1994) have provided detailed discussions of the effects of various pesticides on earthworm abundance. It is generally accepted that most herbicides are not directly toxic to earthworms, but they may influence numbers indirectly by changing plant production, food supply, and microclimate. Interestingly, Mele & Carter (1999b) found that heavy (c.f. recommended) rates of post-emergent herbicides increased earthworm abundance. Some fungicides, such as benomyl, can be very toxic to earthworms and influence them indirectly by altering their food supply. Buckerfield (1993b) showed that the use of fungicides can alter species composition of earthworm populations in S.A. pastures. Fumigants such as methyl bromide and many insecticides (e.g. organochlorines and carbamates) also kill earthworms. However, very few studies have been made along these lines in Australia. Choo & Baker (1998) assessed the influence of endosulfan (insecticide) and fenamiphos (nematicide) on *A. trapezoides* in both the field and lab and showed that growth and reproduction were affected at recommended application rates. A worrying trend in southern S.A. was the increased use of methiocarb baits to control introduced helicid snails which are pests of grain crops and pastures (Baker 1989). These snails are particularly numerous where tillage is reduced and organic matter is retained – just the situation where earthworm numbers are likely to be encouraged. However, a recent trend towards use of metaldehyde baits, which are cheaper and non-toxic for earthworms, is encouraging.

Antiparasitic drugs, such as avermectins, are widely used in grazing ruminants in Australian pastures and residues of these drugs are excreted in the faeces. One of these, ivermectin, has been shown to have serious detrimental effects on dung-inhabiting arthropods, especially larvae of dung beetles and flies (Strong & Wall 1994; Wardaugh et al 1996). Gunn & Sadd (1994) found detrimental effects of ivermectin on the earthworm *Eisenia fetida* in the laboratory, but the few studies that have been made in the field suggest that ivermectin is harmless to earthworms there (Sommer et al 1992). Another group of chemicals, milbemycins, appear to be much less harmful to dung-inhabiting flies and beetles than the avermectins (Strong & Wall 1994; Wardhaugh et al 1996). One of these, moxidectin, has been tested for its effect on *A. longa* in Australia, in both field and lab via sheep and cattle dung (Svendsen & Baker 2002). No lethal or sub-lethal effects were found.

5. Introductions of New Earthworm Taxa

The introduction of earthworms to soils lacking them has resulted in significant increases in plant production in several countries (see Introduction). However, occasional examples do exist where negative impacts have been argued – e.g. James (1991) reported that the introduction of *A. caliginosa* and *O. cyaneum* to tallgrass prairie in the U.S.A. had a negative influence on soil properties through a reduction in the numbers of more useful native species (*Diplocardia* spp.). A simple method for inoculating earthworms into unpopulated soils was developed by Stockdill (1982). This involved cutting shallow sods of soil from heavily populated fields and placing them in unpopulated sites. This method is especially suitable for epigeic and endogeic species and has been adopted successfully by farmers in Tasmania. Butt (1992, 1999) and Butt et al (1992, 1995) have developed an alternative method for mass-producing and distributing deep-burrowing, anecic species.

The rates of dispersal of earthworms following introduction to new habitats have been measured by several authors in New Zealand and Europe (e.g. see Stockdill 1982; Marinissen & van den Bosch 1992; Stein et al 1992 and references therein) and vary between 2-15 m yr^{-1}, according to the fecundities and burrowing behaviours of the different species.

The earthworm fauna in pasture soils in southern Australia is dominated by accidentally introduced species that are now distributed patchily. While edaphic and climatic factors explain much of this patchiness in distribution, it is reasonable to assume that many areas that lack particular species do so because of lack of opportunity to colonise. Increasing the distributions of the most beneficial species through deliberate introductions, to sites where they are thought likely to establish, may prove very profitable. However, few such field introductions of earthworms have been made to date – especially at field scale. *A. caliginosa* and *A. longa* have been introduced into pastures in Tasmania with resultant increases in production (Temple-Smith et al 1993; Garnsey 1994a). Introductions of *A. caliginosa* to irrigated pastures in N.S.W. led to a breakdown of a thick litter mat and a decline in bulk density (Noble et al 1970), and introductions of *Aporrectodea* spp. *and Eukerria saltensis* (Ocnerodrilidae) into irrigated wheat in N.S.W. increased air permeability of the soil (Blackwell & Blackwell 1989).

The distribution of the deep-burrowing *A. longa* is currently restricted (in the main) within Australia to Tasmania (Baker et 1997a). Baker (1998a) used climatic matching software to predict where *A. longa* might colonise within mainland Australia if given the chance, based on regions of the world where it already exists. This corresponded with large areas of south-eastern and south-western Australia (essentially those with > 600mm annual rainfall). Baker & Whitby (2003) have since cautioned that this distribution is no doubt an over-estimate. For example, their research on the environmental factors that control development time for cocoons showed that the length of season during which the soil remains sufficiently moist in much of south-eastern Australia is likely to be inadequate to support viable populations. In addition many soils are currently too acid for *A. longa* to accept. *A. longa* prefers soils with pH > 4.5. Nevertheless, Baker et al (1999a), successfully introduced *A. longa* to several sites in south-eastern Australia (in the short term), and noting its relatively high establishment rate compared with other more widely spread species (e.g. *A. caliginosa* and *A. trapezoides*), concluded that lack of opportunity to colonise was a major reason for its absence. Recent research has concentrated on developing mass rearing methods for *A. longa* (e.g. determining optimum soil type, temperature, soil moisture, pH, food type, population density etc) (G. Baker, unpub. data). The opportunity now exists for private industry (e.g. worm farmers, hitherto concentrating on vermi-composting) to follow up this research and enable greater availability of *A. longa* to land holders.

The possibility also exists to introduce additional earthworm species into southern Australia from climatically matched regions overseas. No deliberate attempts to do this have yet been recorded, although such a strategy was suggested by Barley (1959c) and Lee (1985). Broad-scale surveys and intensive, seasonal monitoring of field populations (see above) suggest that the current fauna in agricultural fields is poorly represented with deep-burrowing species. Virtually all earthworm activity is confined to the top 10 cm or less of soil during winter and spring. The further spread of *A. longa* within Australia will possibly help to redress this limitation of the earthworm fauna, but it is unlikely that *A. longa* will successfully colonise the strictly mediterranean climatic regions. The natural distribution of *A. longa* does not extend into mediterranean regions of countries such as France. Instead, other anecic species such as *Scherotheca* spp. are found commonly there. These latter species might be considered for importation to Australia.

The native European distributions of several of the lumbricid species now found in Australia are broad, ranging from the Mediterranean to Scandinavia (e.g. *A. caliginosa* and *A. chlorotica*). The majority of early European migrants to Australia, who presumably brought these lumbricids with them accidentally (e.g. in potted plants), were mainly from countries with cool, temperate climates, such as the U.K., Ireland and Germany. It is sensible to question the likely suitability of strains of earthworms from such countries, when faced with the warmer and drier habitats in much of southern Australia, and if mediterranean strains of the same species might be more appropriate (Baker 1998a,b). Dyer et al (1998) used PCR-based techniques to at least show that different geographic races of *A. trapezoides* can be recognised within Australia. Perhaps such techniques could also be used to trace back the origins of Australian populations to Europe, check their ecological suitability, and select better ones? We actively select climatically sensible strains / varieties of agricultural plants and bio-control agents – why not also soil fauna?

There are risks attached to introducing new taxa, whether they come from overseas or from elsewhere within Australia. Issues that must be faced include the possibility that the new invaders might compete with the local fauna, disrupt ecosystem processes in non-target areas (e.g. native forests and pastures, compared with improved pastures and croplands) and carry with them undesired diseases. The latter can be controlled through rigorous quarantine procedures. Some preliminary studies have been completed which suggest that *A. longa* is unlikely to invade native woodlands in southern Australia and compete with native earthworms there (Dalby et al 1998a). There is little doubt that *A. longa* will have some impact on the abundance of resident earthworms when introduced into pastures (Dalby et al 1998b; Baker et al 1999a; Baker et al 2002a), but recent studies suggest that this impact is small, and that the overall abundance – and most importantly the functional diversity – is increased .

6. Earthworms in Pastures in Northern Australia

The comments in sections above all refer to knowledge of the distribution, biology and agricultural value of earthworms in southern temperate or Mediterranean climatic zones in Australia. There is very little known of such topics for pastures in northern Australia. Baker et al (1997a) did document the presence of some earthworm species in tropical grasslands, noting they differed from those in the south (e.g. the exotic *Pontoscolex corethrurus*), and indicated that some of the more southern species (e.g. *Aporrectodea* spp.) can be found as far north as southern Queensland. Blakemore (1997) reported that introductions of exotic and native species increased pasture production on brigalow soils by 64% within a year in south-eastern Queensland. In other studies, Friend & Chan (1995) & Chan et al (1997) have shown that native earthworms (e.g. *Heteroporodrilus mediterreus*) can improve the structure (hydraulic properties) of native pasture soils in north-western N.S.W.

7. Earthworms as Indicators of the Sustainability of Agriculture

Earthworms are popularly believed to reflect soil health. They often make up a large proportion of the biomass of the soil fauna and respond numerically to many agricultural management practices (see above). Earthworm abundance and biomass are also correlated with a range of edaphic variables. It is therefore not surprising that earthworms have been suggested as potential indicators of the sustainability of agricultural practices that farmers might use (Oades & Walters 1994; Buckerfield et al 1997).

A useful indicator of sustainability must be attractive to farmers so that they will understand and adopt it, easy to measure reliably, and responsive to environmental change in a timely fashion. Farmers know that earthworms are generally beneficial. However, few are ware of the species they have on their land and, like scientists, they are unclear just how many earthworms they need in their soil (i.e. what are the abundance thresholds they need to aim at ?). It is important that farmers recognise the species of earthworms they have on their farms, realise the varying abilities of species to influence soil properties and plant production, and note the strengths and weaknesses of their resource. Simple keys have been devised for the common earthworm species in Australia that farmers might use (e.g. Baker & Barrett 1994; Mele & Hollier 1995), but these are now out of print and perhaps should be revisited.

Sampling for earthworms, whichever method is used, is notoriously labour intensive and fraught with inaccuracies (Baker & Lee 1992), and for this reason (and others) some (Lobry de Bruyn 1997; Doube & Schmidt 1997; Baker 1999) have questioned the practicality of using earthworms as biological indicators. Soil moisture can vary within short periods of time and greatly affect the numbers of earthworms collected (Baker et al. 19993c). Earthworms are patchily distributed within fields and vary greatly in abundance from one year to the next when no overt changes in management practices occur (Baker et al 1992, 1993b; Baker 1999). Spatial patterns vary between species (Baker 1999). Farmers are busy people, but they must take care to collect sufficient samples to make their data meaningful and enable detection of differences in abundance through time and space. Some earthworms have large reproductive potential (e.g. epigeic species) but the earthworms that predominate in Australian agricultural fields probably do not (Lee 1985). While drastic physical or chemical disturbance might quickly reduce earthworm numbers, numerical recovery may well take several years.

The fact that the earthworm fauna of Australian agricultural habitats is dominated by introduced species raises an immediate question : how far have these species spread to occupy sites suitable for them ? The answer is not known, but it seems likely that there are many sites yet to be occupied. More than 40% of pastures in one region of western Vic. lack *A. trapezoides*, but bot no good reason other than lack of opportunity to colonise can be given for its absence from these pastures. While the presence of large numbers of a diverse community of earthworms can only be a healthy sign, there is a strong risk that low numbers or indeed absence of earthworms might be misinterpreted as a “problem” at a particular site when the real problem is not with the soil per se but the chance of earthworm dispersal to it. Some seemingly “healthy” soils in Australia lack earthworms (e.g. some kraznozems). That is not to say that these soils would not be more productive with the arrival of appropriate species of earthworms!

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7.6 APPENDIX 6. Dung beetles in Australian pastures

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Introduction

The pollution of Australian pastures by the dung of cattle, sheep and goats, combined with the absence of an effective indigenous dung beetle fauna, has created an ecological imbalance which the introduction of exotic dung beetles to Australia has, in part, redressed over the past 30 years.

Dung beetles have specific climatic requirements and exotic species are now established in summer rainfall, even rainfall, and winter rainfall regions of Australia (Doube et al. 1991)**.** Dung beetles also show distinct preferences for different types of dung; there are beetles which prefer herbivore (cattle) pads or pellets (sheep, goats), and others which select omnivore and carnivore dung (Hanski and Camberfort 1991). The current suite of introduced dung beetles comprises those that prefer cattle dung.

The intended benefits (Waterhouse 1974) of introduced dung beetles were
to reduce pasture spoilage,
to bury the dung and so improve the fertility of soils and
to control dung breeding flies and other pests

Despite some encouraging preliminary studies (Bornemissa 1976) and much conjecture (eg Curry 1987; Edwards and Aschenborn 1987; Davis 1996), the evidence for broadscale agronomic benefits of dung beetle activity does not exist. In contrast, introduced dung beetles have undoubtedly caused a dramatic and permanent reduction in the abundance of the dung breeding bush fly in the moister temperate regions of southern Australia (Ridsdill-Smith 1998). Dung beetle activity also reduces the survival of infective larval helminths (intestinal parasites) in dung (Bryan and Kerr 1989).

Triple bottom line accounting for has created an imperative for Australian graziers to accept responsibility for off-farm pollution caused by farming practices.
An additional potential benefit of dung beetles relates to the control of off-farm water pollution. Pollution of water in catchments with organic residues and pathogens (eg the human pathogen *Cryptosporidium*) originating in herbivore dung is a newly recognised and important environmental threat (Robertson et al. 2000). The capacity of introduced dung beetles to reduce this problem needs be explored.

Establishment and dispersal of dung beetles

About half of the 50+ exotic species brought to Australia by CSIRO in the 1970s and 1980s have become established, but most of these are far from reaching their natural limits in Australian pastures. In many pastures, few or no exotic dung beetles are yet established. A significant research effort is currently directed to mapping the present distribution of the established species in Queensland (Elphinstone 2002), but there is little systematic analysis of the status of introduced dung beetle species in other regions of Australia.

The cropping and redistributing of beetles to regions in which they are likely to prosper is currently being undertaken by commercial private businesses which crop beetles in WA (John Allen) and NSW (John Feehan) and export them to other regions in Australia. There is substantial grazier demand for dung beetles and some regional beetle introduction projects are being supported by local authorities (eg the Adelaide Hills Environment Protection Authority is assisting the Fleurieu [Peninsula] Beef Group to introduce dung beetles).

Only one exotic dung beetle (*Copris incertis*) has been introduced to New Zealand (Blank, Black and Olson 1983; Cameron et al. 1987). The case for introducing dung beetles to New Zealand is clear (Dymock, 1993), but no introduction program has been initiated.

Dung beetle activity and dung burial in Australian pastures

Although in some regions and at some times of year there are periods of high beetle activity resulting in substantial dung burial (Doube et al 1991), such instances are, at present, rare. It is encouraging that in Australia levels of beetle abundance and dung burial are, at times, significantly higher than recorded in comparable environments overseas (Doube 1991). This may be due to a lack of natural enemies of the dung beetles in Australia.

The gaps in seasonal activity of dung burial by beetles need to be documented by systematic dung beetle monitoring in a series of key environments, identified by climate matching.

Current beetle distributions and gaps

Dung beetles have become much more widely dispersed since CSIRO closed its dung beetle program 15 years ago (Doube et al 1991). Nevertheless, it appears that only a small proportion of the pastoral regions of Australia have even a few dung beetle species established (Tyndale-Biscoe 1990). A national dung beetle survey should be conducted to establish the current limits to the distribution of established species.

Types of dung burial activity, breeding activity and soil profiles

Three types of dung beetles are recognised: ball rollers (which roll dung away from the dung pad), tunnellers (which bury dung beneath the dung pad), and endocoprids (which breed within the dung pad) (Doube 1991). The majority of the introduced beetle species established in Australia are tunnellers (Tyndale-Biscoe 1990).

Newly emerged tunnelling dung beetles feed on the juices in dung until their ovaries are mature and are ready to produce eggs. This maturation feeding generally occurs in a shallow burrow. Egg laying in buried dung takes place in deeper burrows (up to 1 m deep). Breeding beetles consequently move much soil to the surface in the process of excavating the access tunnel and the breeding chamber. Since mature cattle produce about 25 litres of dung daily, dung burial activity has a substantial capacity to alter soil profiles, increasing the depth of top soil over time. This effect needs to be quantified.

Seasonal activity of dung beetles

Dung beetles have specific seasonal activity patterns. Dung beetle communities commonly contain a series of species that becomes progressively active (colonising dung) as the seasons pass (Hanski and Camberfort 1991)**.**

For example, in the Mediterranean regions of Australia, there are exotic species whose adult activity (ie dung burying activity) is primarily restricted to one or two seasons of the year.

Each of these groups (eg winter-active, or spring-active or summer active) needs to be represented to achieve effective year-round dung burial. An appropriate suite of species has yet to be established most localities in Australia.

Water quality: organic pollution and pathogen contamination

Pollution of water in catchments with organic residues and pathogens (eg the human pathogen *Cryptosporidium*) originating in dung, especially that of cattle, is a newly recognised and important environmental threat (Mathison and Ditrich 1999; Anon. 2002) The contaminants are carries across the landscape surface in free water running off pastures and possibly also through soil (ie beneath the surface).

The capacity of dung beetles to reduce this problem by removing dung (and its pathogens) from the soil surface and by increasing soil permeability and so reducing the run-off of contaminated waters needs to be examined.

Quarantine and a dung beetle register

There is no systematic recording of the deliberate dispersal of dung beetles within Australasia and a central register for documenting this process is necessary. This is particularly important if the beetles have the capacity to spread mammalian disease.

Quarantine restrictions on dung beetle movement within Australia do not exist and yet there is a danger that diseases whose infective stages are associated with bovine dung, for example Johne's disease and *Cryptosporidium* (Mathison and Ditrich 1999) may be dispersed along with the dung beetles. The dangers and liabilities associated with this issue need to be addressed.

Agrochemicals threaten dung beetles

The use of some systemic anthelminthics poses a serious threat to dung beetles because the contaminated dung of treated cattle can be lethal to both the adult and juvenile dung beetles (Wardhaugh and Ridsdill-Smith 1998). Some recently developed compounds are claimed to be 'dung beetle friendly' and not kill beetles.

The strategic use of anthelminthics that takes account of the seasonal activity patterns of beetles may provide a functional solution. This option is currently being explored.

Do we need to introduce additional species?

There are numbers of additional exotic dung beetle species whose biology makes them prime candidates to augment species already established in Australia. Nevertheless, a decision about which, if any, of these species need to be introduced to Australia should wait until the current suite of introduced dung beetles have largely reached their natural distribution and abundance levels.

Conclusion

The establishment of exotic dung beetles in Australia has been highly successful, but most species have not yet reached their natural limit, and their dispersal to other regions should be promoted primarily through grazier organisations assisted by specialist advisers. A registry should be established to record deliberate dispersal of beetles in Australia. The dangers associated with the lack of dung beetle quarantine procedures within Australia need to be examined.

The highest research priority should be given to establishing the capacity of dung beetle species to reduce organic and pathogenic pollution of water moving from pastures into water catchments. Interdisciplinary collaboration should be established with support from agencies responsible for water quality, pasture management and dung beetles.
Before additional research is directed towards mapping, cropping and redistributing established species, the agronomic benefits of dung beetles need to be established. The mechanisms responsible (eg, improved infiltration and storage of water, elevated soil organic status, deeper soil profiles) need to be documented so that the most beneficial species can be promoted.

Recommended research topics in priority order

The effect of dung beetle activity on catchment water quality
The effect of dung beetle activity on plant growth
The effect of tunnelling and dung burial activity of dung beetles on soil properties
The current and potential distribution of established beetle species
Quarantine precaution governing the dispersal of dung beetles
A register documenting the deliberate dispersal of dung beetles
Strategic use of anthelminthics to minimise collateral dung beetle mortality

References for Appendix 6

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7.7 APPENDIX 7. Approach to Research