Chapter 15

Harnessing the benefits of soil biology in conservation agriculture

Vadakattu Gupta, Margaret Roper and John Thompson

Soil biology and ecology in conservation agriculture

"Soil, the 1 m skin of the earth, sustains all life forms in the terrestrial ecosystem and is vital to the very existence and substance of human life" (Dick 2018). Soils function as biological entities due to the microbial communities that exist within them. It is estimated that in 1 kg of soil, there are more than 1 billion bacteria and >2 km of fungal hyphae. More than 95% of soil microbial species are non-culturable, but metagenomic analysis of nucleic acids is transforming our ability to understand the breadth and diversity of soil microbial communities and their functional capabilities.

Soil microbial communities are dependent for the most part on food sources, water and oxygen. In Australian soils, which are low in soil organic matter, spatial heterogeneity results in more concentrated communities associated with microsites such as plant roots (rhizosphere) and decomposing residues (detritusphere) which support approximately 60% of all microbial life in surface soils. In the rhizosphere, carbon (C) and other nutrients and water are supplied by rhizodeposition with above- and below-ground crop residues being major sources of C inputs in agricultural soils. Microbial communities in the rhizosphere generally originate from the general soil but spatial isolation and minimal food sources in the soil limit their proliferation and activities. In the rhizosphere, interactions among microorganisms and plants are generally mutualistic. Apart from food and nutrients supplied by plants, microorganisms benefit from interactions with each other and provide benefits to the plant by transforming nutrients to available forms or by competing with or suppressing plant pathogens. This is a somewhat simplistic view of plant-microbial interactions: in reality relationships are more complex (Roper and Gupta 1995). Some aspects of this complexity are addressed in this chapter.

Conservation agriculture (CA), as defined by FAO, and technologies that have expanded from it, has four basic elements that we focus on in this Chapter:

- reduced or no-tillage (no-till);
- retention of plant/crop residues;
- diverse rotations; and
- precision agriculture including controlled traffic.

Each of these elements greatly impacts soil microbial communities, their function and system productivity. We first consider some of these impacts in the context of soil ecology and the soil food web under Australian cropping systems.

Ecological changes associated with conservation agriculture - soil physico-chemical properties

Despite the large numbers of microorganisms in the soil, they often exist in a biological desert. This is due to the small size of microbial (e.g. bacteria) cells in relation to the volume and surface area of soil particles. This can make it difficult for microorganisms to operate as a community as many of them need each other in order to carry out ecosystem services within the soil. For example, many organisms require C as an energy source to transform other nutrients; non-symbiotic nitrogen (N) fixing bacteria may rely on cellulolytic microorganisms for the supply of more available forms of C, and N mineralisation is more rapid with a complete web of soil organisms. Such mutualistic interactions are enabled through co-location on or within soil aggregates and pore networks. Microorganisms frequently contribute directly to soil aggregate formation through the production of polysaccharides that bind soil particles and through fungal hyphal networks that hold multiple aggregates together (Figure 1). However, cultivation, particularly intense disturbance, can disrupt aggregates and soil structure, and

therefore compromise microbial functions that supply nutrients to plants and provide protection from pathogens.

In Australia, adoption of CA has resulted firstly in significant increases in the labile and biologically available pools of soil organic matter. The particulate organic C pool typically accounts for 20-35% of total C especially in the surface (0-5 cm) soil layer. This particulate organic matter forms centres of microbial activities supporting both beneficial and deleterious microorganisms (plant pathogens). Secondly, reduced tillage has increased the gradient of microbial biomass distribution in the soil profile with the majority of microorganisms (50-75%) and soil biological activity concentrated in a thin surface layer to 5 cm depth (Gupta *et al.* 1994, Roper *et al.* 2010). In addition, in rainfed cropping regions, optimum conditions for microbial activity are short and infrequent because surface soils are generally prone to cycles of wet periods separated by long dry periods often under hot conditions. CA alters soil moisture retention properties favourably, albeit for short periods, thereby promoting optimal periods for microbiological functions (Gupta *et al.* 2011).

CA has facilitated the development and maintenance of soil aggregates, particularly larger and more fragile aggregates where organic matter is protected, and microbial processes proliferate (Six *et al.* 2000). Aggregate turnover is reduced under no-till compared with cultivation resulting in the formation of stable microaggregates in which C is stabilised and sequestered in the long term. Soil aggregates support the function of diverse populations of soil microflora by providing a range of conditions such as oxygen gradients, and very specific habitats (*e.g.* non-symbiotic N fixing bacteria which require lowered oxygen for nitrogenase activity). Not only does a well-structured soil promote water infiltration itself, but under reduced tillage or no-till, old root pathways remain intact as conduits for water entry to the soil. This mechanism is especially critical for water infiltration and crop production on water repellent soils which occupy more than 10 million hectares of agricultural land in southern Australia and Western Australia (WA) (Roper *et al.* 2013).
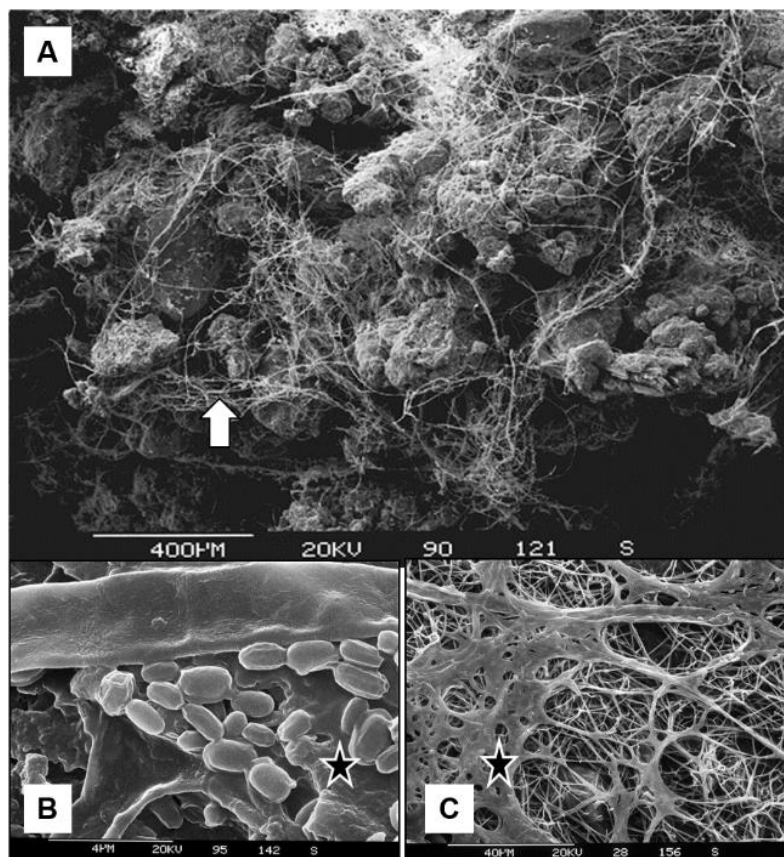
Figure 1. A network of fungal hyphae (arrow) holding soil particles to crop residues as part of soil aggregate formation (A), microbial glues (★) produced by bacteria (B) and fungi (C) help bind soil particles into stable aggregates (Gupta VVSR, CSIRO, unpublished).

The improved soil structure and stability in CA systems facilitates better drainage and water holding capacity, reducing the effects of water logging and water stress. As well, above-ground residues form the focal point for aggregate formation and fungal hyphal networks resulting in reduced wind erosion. Furthermore, crop residues protect soil surfaces and microbial communities from extreme temperatures and act as a surface mulch to reduce water losses under dry conditions (Ward *et al.* 2013). In wet environments, this may contribute to surface water-logging, but this may be offset by improved water infiltration and drainage in well-structured aggregated soils. Biopores, formed by macrofauna (earthworms, termites and ants) and plant roots, are conduits for water, oxygen and nutrients to subsoils, and have been shown to play an important role in the ability of plant roots to access water and nutrients from deeper layers of the soil profile in hostile or compacted soils (White and Kirkegaard 2010). Crop residues feed soil fauna that build these structures which are protected by no-till. The presence of old decomposing roots in close contact with new roots increases the interaction between microorganisms in the rhizosphere and the detritusphere creating a biologically modified environment with implications for both beneficial and deleterious biological functions.
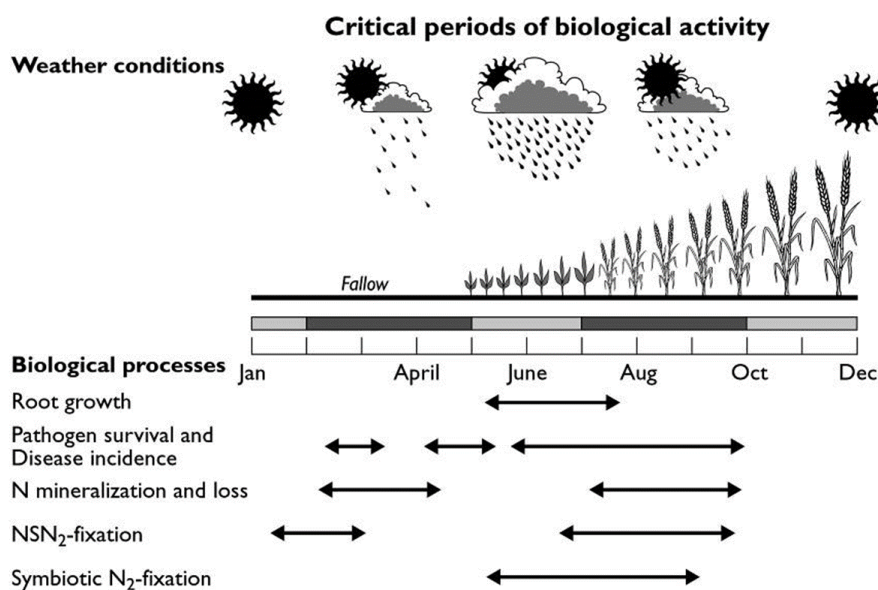
Figure 2. A conceptual model describing the significance of soil biological processes and their impact within the farming system in a Mediterranean-type climate in the southern and Western Australian cropping regions, where winter rainfall predominates (modified from Gupta *et al.* 2011).

Diversity of agro-ecological zones, cropping systems and biologically-optimal periods

Several edaphic and environmental factors contribute to microbial diversity and function in different agro-ecological zones. Winter rainfall predominates in Mediterranean-type environments in southern agro-ecological regions creating biologically optimal periods in terms of microbial activity, nutrient mineralisation and pathogen survival during non-host periods. Hot dry summers in this region severely limit microbial activity (Figure 2).

In northern New South Wales and Queensland, summer dominant rainfall coupled with warm conditions promotes active microbial communities culminating in rapid decomposition of C resources and significant biological activity by co-located microbial communities such as cellulolytic microorganisms and non-symbiotic N fixing bacteria (Roper and Gupta 2016).

Much of the agricultural regions of southern Australia and WA, with winter dominant rainfall patterns, are cereal dominated with wheat being the primary crop grown and other major rotational winter crops

being barley, canola, field pea and lupin. In the subtropical region of northern NSW and Qld, winter crops such as wheat, barley and chickpea as well as summer crops such as sorghum, mungbean and cotton are grown. The third element of conservation agriculture is the use of diverse rotations. However, growers tend to focus on crops that are most profitable, sometimes with increased risk of disease or weed infestation due to limited rotation cycles. For example, in south and WA, repeated cereal/canola crops are common. Considerable benefits in ecosystem function could be achieved through greater plant diversity which has been shown to increase microbial diversity, minimise the proliferation of soil-borne pathogens (Yukicevich *et al.* 2016) and increase biological resilience. Therefore, research on alternative crops suitable for each region is critical for stable and profitable conservation agriculture systems.
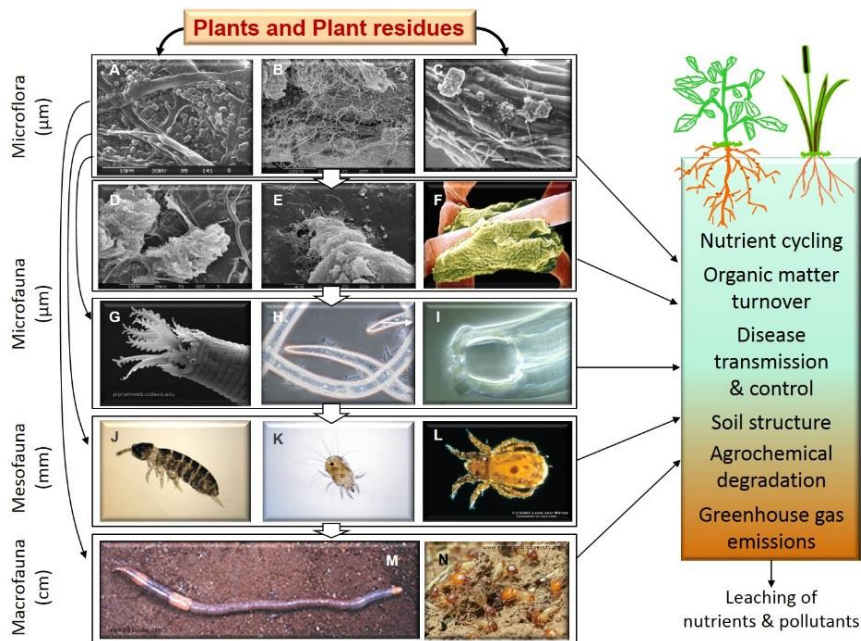
Figure 3. A pictorial representation of the soil detrital food web in agricultural systems: (A) bacteria, (B) fungi, (C) arbuscular-mycchorizal fungi (AMF), (D) bacterial feeding amoeba, (E) testate amoeba, (F) mycophagous amoeba, (G) bacteriovore nematode, (H) fungivore nematode, (I) predatory nematode, (J) collembola, (K) mesostigmata mite, (L) mite, (M) earthworm, (N) termite.

Microbiology and soil fauna – food web and trophic levels

The soil food web consists of organisms of many different sizes and activities, from earthworms and smaller soil animals to fungi and bacteria (Figure 3). The soil food web ecology with its emphasis on how the biota community is assembled has the potential to act as an integrating concept across conservation biology, community ecology and provision of ecosystem services (Coleman *et al.* 2018).

Soil organic matter, whether derived directly from plants or from animals, drives the soil food web as a basic source of energy. Soil microflora (bacteria, fungi and protozoa) are the principal decomposers of organic matter, whereas the soil fauna, and their interactions with other soil organisms, impact on nutrient (N, phosphorus (P) and sulphur (S)) cycles. While microfauna feed directly on microflora, mesofauna feed on detritus, rich in microflora, and thus are key in microbial turnover (both beneficial and pathogenic) and nutrient cycling. Macrofauna are known as ecosystem engineers and fragment plant residues thereby stimulating microbial activity. They can create biopores and help redistribute organic matter and microorganisms, especially under reduced tillage and crop residue retention.

Under CA, soils are extremely heterogeneous both in terms of food source and habitat suitability for various organisms, resulting in hot spots of activity (*e.g.* detritusphere, rhizosphere, aggregatusphere,

drilosphere and porosphere) all of which support >90% of total soil biological activity (Beare *et al.* 1995). Larger amounts of soil organic matter generally support greater soil food web activity, if other conditions including soil moisture are suitable. Too dry and there will be little activity; too wet and there will be a lack of oxygen, leading to a reduction in activity and a shift towards anaerobic organisms (usually bacteria).

Harnessing benefits from micro-organisms – functional perspectives

Adoption of CA has enhanced soil habitat structures and the availability of food sources (C) from crop residues for food web activities including key functions such as C turnover and sequestration, nutrient cycling, disease suppression, aggregate structure and stability and community resilience (Coleman *et al.* 2018). Evidence exists for changes, following the adoption of CA in microbial and faunal communities (beneficial and pathogenic) in all soil types and from all agro-ecological regions of Australia, both in rainfed and irrigated agricultural systems.

Stubble retention and reduced tillage has shifted microbial communities towards a fungal-dominated food web compared with bacterial dominated communities in systems with cultivation and stubble removal. The time taken for such changes to eventuate varies with soil type, rainfall intensity and annual distribution, and crop residue management. Whilst immediate changes in nutrient cycling and plant pathogen dynamics can occur, development of disease suppression may take 5-7 years (Gupta *et al.* 2011). Effects of CA on the genetic diversity of bacterial and fungal communities may take longer to materialise (Gupta *et al.* 2010) and it can take 20 years or more to realise significant increases in soil organic C (Sanderman *et al.* 2010). Recent evidence suggests that the rate of C sequestration under CA can be accelerated by manipulating the stoichiometry of C inputs (C:N:P:S ratios) which influences the microbial C turnover (*i.e.* microbial assimilation efficiency, see Chapter 16).

Reduced tillage systems also introduce a significant stratification in the abundance, diversity and activities of heterotrophic organisms compared with that in conventional tillage systems. The effects of this stratification on stubble and soil-borne diseases such as Fusarium crown rot, rhizoctonia and foliar diseases have been observed in all agricultural regions (see Chapter 11).

The main limitation for microbial functions in soils is a lack of C or food as an energy source for microbial activity. CA provides such a source through stubble retention but often it is inaccessible for many microorganisms and requires decomposition to available forms. Microorganisms responsible for decomposition of organic matter are diverse as described above, and are universal within soil communities. However, their efficiency and community size may be limited due to historically low organic matter inputs. After a few years of stubble retention within CA, however, decomposer microbial communities respond to inputs of organic matter and rates of decomposition increase, although rates of change can vary with quality and quantity of stubbles or if stubbles are left standing or in contact with the soil (Adl 2003).

Crop residues and their decomposition products drive the many microbial functions in soils. In the following sections we focus on the benefits of CA for some aspects of N cycling including N mineralisation and non-symbiotic N fixation, the role of arbuscular-mycorrhizal fungi, disease suppression of necrotrophic fungi, nematodes, earthworms, termites and other soil fauna.

N cycling

Mineralisation / immobilisation Nitrogen mineralised from the decomposition of soil organic matter and crop residues makes a substantial contribution to crop N uptake (Angus and Grace 2017). The mineralisation of organic substrates (soil organic matter and crop residues) and the release of nutrients into soils is regulated by heterotrophic activity within the decomposer microbial community and microbial turnover. Microbial processes such as depolymerisation of SOM, ammonification, nitrification, N fixation and denitrification all control the rate and timing of N mineralisation and subsequently plant available mineral N in soils. Microflora-microfaunal (*e.g.* protozoa and nematodes) interactions modulate microbial turnover in soils and thus the release of mineral N previously immobilised within the microbial biomass.

Following the adoption of CA, increased biologically available C and improved soil structure promote microbial diversity, growth and activity including N cycling. Changes in the short-term flux of labile SOM pools (*e.g.* dissolved OM and particulate organic matter C) due to stubble retention significantly influence biological N cycling and N availability. Soil microbial biomass (MB), the mass of living components of soil organic matter, is both a source and sink of biologically mediated nutrients. Changes in MB due to modified management, seasonal conditions and the rhizosphere significantly impact net N mineralisation and microbial immobilisation. MB-C accounts for 1.5-3.0% of soil organic C and MB-N for 2.0-5.0% of total N. In cereal crops, MB generally increases (by >2-fold) from sowing to the end of flowering after which it reduces depending upon seasonal conditions. Therefore, increased MB and the accompanying N tie-up (immobilisation) associated with stubble retention may reduce N availability to cereals, especially during the early crop growth stages. However, N tie-up is only a temporary constraint as the immobilised N will be released through microbial turnover, generally later in the crop season in spring when rapid crop growth and development occur.

CA can alter the composition and abundances of microbial communities involved in N mineralisation and immobilisation, and also influence fertiliser N use efficiency. Stubble retention and no-till alter enzyme activity, with increasing activity associated with stubble incorporation in the short-term due to associated changes in microbial composition and microbial turnover (Ladd *et al.* 1994, Hoyle and Murphy 2006). Both the rate and timing of N mineralisation regulate plant available N in soils and, therefore, crop growth (Gupta *et al.* 2011). In dryland cropping in Australia, the effects of stubble treatment on gross N mineralisation, nitrification and immobilisation are seasonally dependant. For example, in the stubble retained and no-till systems, N immobilisation exceeds nitrification and N mineralisation in the absence of plant demand, during April to June, provided soil moisture is available. Therefore it is important to consider microbial immobilisation of N when planning the fertiliser N needs of a following crop, particularly for cereals in CA systems.

Crop residue quality influences N supply from decomposition. For example, intensive cropping, especially intensive cereal cropping, instead of mixed farming where crop rotation with legume pastures is common, has generally resulted in a decline in the quality of crop residues and consequently N mineralisation. Cereal crop residues have high C:N ratios (100:1) compared with N-rich legume residues with C:N ratios between 15 and 25. Crop residues with a C:N ratio >22:1 generally result in immobilisation of mineral N within the microbial biomass.

Legume crop residues can make a significant contribution to the N needs of following cereal crops. For example, an apparent recovery of 30±10% of legume residue N by following wheat crops was observed over 20 legume treatments in dryland experiments conducted in eastern Australia (Peoples *et al.* 2017). Cereal stubble is not a major source of N for following cereal crops but should mainly be seen as a source of C for microbial activity. In no-till systems, only 1-6% of the N requirement of cereal crops is derived from the previous year's wheat stubble (Gupta *et al.* 2017). Non-cereal break-crops (*e.g.* legumes and canola) also help cereals to access the soil mineral N pool better, through improved root health and by reducing cereal root diseases (Gupta *et al.* 2011).

Traditionally, the capacity for N mineralisation in soils was estimated as a fraction of SOM-C or total N. However, in CA, where seasonal variations in MB occur, N that can be mineralised from SOM and crop residues and N immobilisation need to be considered to estimate N supply potential at the beginning of a crop season.

Non-symbiotic N fixation Non-symbiotic N fixation (NSNF) by free-living N-fixing bacteria can provide economic and environmental sustainability to N management in Australian agriculture. Non-symbiotic N fixation refers to N fixation by bacteria (autotrophic and heterotrophic) growing independently in soil utilising the products of decomposed plant residues, in termite mounds, or in close association with plant roots without forming nodules (Roper and Gupta 2016). With the increased adoption of intensive cropping and larger areas under consecutive cereal crops (>50%), NSNF has the potential to contribute substantially to the N requirements in cereal crops.

Adoption of CA has made the soil habitat more favourable for NSNF. It increases the number of microsites with available C and the number of aggregates, especially macro-aggregates, which are critical for the development and maintenance of microsites of reduced oxygen tension required for NSNF by free-living bacteria in soils. Any increase in soil disturbance reduces aggregation, reduces soil C and disrupts the soil pore network by which stubble decomposing organisms and N-fixing bacteria interact. As a result, NSNF under reduced tillage is characteristically higher than in cultivated soils (Roper and Gupta 2016). However, biological changes in NSNF in response to adopting CA can take several years to develop.

The availability of C as an energy source is critical for NSNF. Crop residues are 50-70% (dry weight) cellulose and hemicellulose which, after decomposition, can be used for NSNF. As a result, rates of NSNF are proportional to the amount of crop residue and how quickly it is decomposed. In cereal crops under CA, conserved aggregates and microsites promote additional inputs of N by free-living N-fixing bacteria utilising root exudates as C sources, particularly during rapid crop growth in spring when soils are wet and temperatures are favourable for activity.

Genetic profiling (*nif*H gene sequencing analysis) of N-fixing bacteria in soils under cereal crops and under CA in QLD, NSW, South Australia (SA) and WA identified a diverse group of N-fixing bacteria (>110 genera), but these varied according to region, soil type and environment, and cereal crop varieties (Gupta *et al.* 2014). This indicates a significant potential for N inputs from NSNF. Estimates of NSNF in soils from cereal fields, measured by a laboratory-based incubation (^{15}N isotope) assay, range from 0.2 to 1.5 kg N/ha/day in sands and sandy loam soils in low to medium rainfall regions of southern Australia and WA to 0.5 to 2 kg/ha/day in clays and loamy soils in high rainfall regions (Gupta *et al.* 2014). Amounts of NSNF increase with increasing % clay content and are reduced by extremes of pH (Roper and Gupta 2016). Clays are important in stabilising aggregates and creating micro-aerobic microsites needed for NSNF. Warm and wet soils are most favourable for NSNF and therefore, regions with summer rainfall favour NSNF. Mineral N concentrations above 25 kg N/ha in surface soils can reduce NSNF, but this varies with soil type.

Under CA, populations of soil fauna such as ants (and termites) and earthworms are generally more abundant. Significant amounts of N fixation can occur in the guts of termites and other arthropods, (4-10 kg N/ha/year, Roper and Gupta 2016), but these amounts can differ according to crop rotations, and the quantity and quality of crop residues.

Arbuscular-mycorrhizal fungi – P and other nutrients

Arbuscular-mycorrhizal fungi (AMF, Phylum Glomeromycota) form symbiotic relationships with plants and are important in the health of many crop species functioning in the efficient acquisition of plant nutrients, especially P and zinc (Zn), from the soil. They colonise the root cortex of plant species in 80% of plant families (Gianinazzi *et al.* 2010) including most crop species, with notable exceptions being canola and lupin. AMF are obligately dependent on living plant roots for their nutrition and reproduction. Large spores are produced by AMF on external hyphae in the soil where they survive between annual host crops.

Because of their extensive hyphal networks in soil, the adoption of CA with reduced or no-till has been beneficial for AMF and their activities. However, because AMF live as symbionts of host plants, long periods of plant-free fallow and/or non-host crops, can cause the decline in viable AMF propagules, resulting in poor colonisation of the next crop and plant nutrient deficiencies known as 'long fallow disorder' (Thompson 1987). The extent to which a crop suffers from diminished AMF depends on the mycorrhizal dependency of the crop species, where relative mycorrhizal dependency is the % decrease in biomass or seed yield of plants grown without AMF compared with plants grown with AMF. For example, in a field experiment with the highly mycorrhizal dependent crop linseed, the uptake of soil P and Zn was linearly dependent on the level of AMF colonisation of the roots, and plants without AMF produced only 15% of the biomass and 22% of the seed yield of plants with AMF (Thompson *et al.* 2013). Most crop species grown in the northern grain region obtain significant benefit from the AMF symbiosis (Thompson *et al*. 1997).

Traditional methods of deliberate long fallowing were beneficial to subsequent crop growth through increased storage of soil water and mineral N in the soil profile, due to microbial decomposition of soil organic matter, and reduction in the inoculum load of some soil-borne pathogens. However, fallow land in the northern Australian grain region, managed by burning crop stubble soon after harvest, ploughing and then cultivating after every rainfall event to control weeds, was detrimental to survival of AMF. The adoption of CA has been beneficial to survival of AMF. Furthermore, CA has led to greater infiltration of rainfall and storage of soil water with surface mulch keeping the soil at sowing depth wetter for longer; this has provided more sowing opportunities for intensification of cropping and a reduction in the length of fallow periods. Rather than fixed rotations, northern region growers tend to follow opportunity cropping, sowing a crop when soil moisture reaches a threshold. For example, growers on the Darling Downs, Qld, double-crop by sowing chickpea soon after sorghum harvest if rainfall has been substantial. Such a sequence maximises the level of AMF inoculum for the chickpea crop with benefits of early P inflow into the roots aiding N fixation by the *Mesorhizobium* bacteroids in the root nodules. Similar benefits can be obtained by double-cropping mungbean soon after wheat harvest. Because of the variable climate in the northern region it is not always possible to follow optimum rotations. For example, where drought enforces long fallow, growers can utilise knowledge of mycorrhizal dependency of the various winter and summer crops as well as the ability of different crop species to build up AMF spore numbers in the soil when choosing crops and fertilisers (Thompson *et al*. 1997, Owen *et al*. 2010). Practices that promote early colonisation with AMF of the root systems of mycorrhizal-dependent crops will help in early crop biomass production and better weed competition. However, the apparent lack of positive growth response to AMF in wheat and some other winter crops in rotation experiments in the southern grains region was ascribed to low soil temperature ($<10˚C$) in the two months after sowing, resulting in slow crop growth and poor growth of external AMF hyphae in the soil (Ryan and Kirkegaard 2012).

Recent developments in DNA methods to quantify AMF inoculum levels in soil (PREDICTA®B service, Ophel-Keller *et al*. 2008) have allowed a better understanding of the effects of CA including crop rotation, fallowing and tillage practices on AMF and crop growth. For example, it has identified (i) the dominant AMF groups (clades) in different agricultural regions; (ii) effects of non-mycorrhizal crop types (*e.g.* canola) and long fallow in Vertosols of northern region, and (iii) effect of pastures under CA on AMF levels in SA.

Disease suppression

Suppression of diseases caused by necrotrophic fungal pathogens Biological suppression generally refers to the reduction of the incidence or severity of disease even in the presence of a pathogen, host plant and favourable climatic conditions for the disease. Disease suppression can also occur when soils become inhospitable to the pathogen itself, referred to as pathogen suppression (Cook 1982). Adoption of CA has influenced microbial C turnover and developed agronomically useful levels of disease suppression in cropping soils (Roget *et al*. 1999, Gupta *et al*. 2011). High levels of disease suppression, which can result in minimal or no disease constraints to plant growth and productivity, have been reported from a variety of cropping systems worldwide including in farmer fields and experimental sites in Australia (Gupta *et al*. 2011). Suppressive soils can be differentiated into two categories. 'General suppression' refers to the inhibition of pathogenic populations, and is related to either the activity of the total microflora or diverse microbial-faunal interactions. In contrast, 'specific suppression' refers to the activity of specific groups of microorganisms (antagonists), such as suppression of take-all of wheat (caused by *Gaeumannomyces graminis*) by *Pseudomonas* species, as demonstrated under CA in WA and SA (Cook and Rovira 1976). It is now evident that the level of disease suppressive activity against soil-borne fungal diseases under CA is a function of the population, activity and composition of the microbial community (Gupta *et al*. 2011, Penton *et al*. 2014, Hayden *et al*. 2018). All soils have an inherent level of suppressive activity, but this level can be significantly modified by farm management practices.

It was considered that soils low in fertility in lower rainfall regions of Mediterranean-type climates may not support suppressive microbial communities. However, agronomically effective levels of disease

suppression in such environments have been demonstrated in long-term field experiments in SA (against rhizoctonia bare patch of wheat, caused by *Rhizoctoniasolani* AG8, and take-all) and subsequently in farmer fields in SA and WA (Gupta *et al.* 2011, Huberli *et al.* 2013). Long-term adoption of CA was one of the key factors that has led to the improvement of disease suppression capacity. For example, in field experiments in SA, disease suppression increased over a period of 5-10 years following a change to CA practices (*e.g.* full stubble retention, limited grazing and higher nutrient inputs to meet crop demand) and complete control of the soil-borne diseases rhizoctonia bare patch and take-all was observed within 10 years, under a range of rotations including continuous cereal, cereal-grain legume and cereal-pasture (see review by Gupta *et al.* 2011).

The successful control of many soil-borne plant pathogens involves management of the pathogen at a combination of different microsites (*e.g.* inoculum source and rhizosphere) in soil and at different time periods (pre-season or in the presence of the susceptible plant). Therefore, *in situ* enhancement of natural disease suppression may be more effective than adding inoculants (Cook 2007). Suppressive ability is a continuum and all soils have some potential for disease suppression. Management practices that supply higher levels of biologically-available C over long periods (>5-7 years) and maintain higher levels of microbial C turnover can result in changes to the composition and activity of the soil microbial community and consequently increase suppression. Management and biotic factors that promote disease suppression are:

- monoculture of host crops over a number of years resulting in increased populations of specific biocontrol agents;
- antibiotic producing/antagonistic microflora and non-pathogenic variants;
- modification of physico-chemical properties of soil;
- addition of composts or other organic manures;
- crop rotations involving crop types that promote specific microbial communities;
- crop residue retention and appropriate tillage treatments;
- addition of large amounts of simple substrates; and
- continued addition of C inputs to support higher levels of C turnover over a long period or multiple seasons.

Suppressive ability is not a fixed property of a soil but can be acquired and maintained at a level beneficial to crops (Roget *et al.* 1999, Gupta *et al.* 2011). This means that productivity losses from root diseases under CA can be reduced, and high water use efficiency attained without expensive and variable chemical controls.

Harnessing beneficial functions from soil fauna

Microfauna - Nematode communities

There are about as many nematode species (Phylum Nematoda) in nature as there are insect species, and nematodes can be found in all ecological niches on the planet. Plant parasitic nematodes occur in the soil and invade the roots of plants using lytic enzymes and the thrusting of their stylet (needle-like mouthparts) to breach cell walls. They include ectoparasitic and endoparasitic nematodes. The majority of nematode species in soil are non-plant parasitic, but feed on other soil organisms and are termed free-living. They form different trophic groups which are adapted to feed on various microorganisms, *i.e.* bacterivores, fungivores, predatory nematodes and omnivores, which can be predatory but in the absence of suitable prey can also feed on bacteria and fungi. Free-living nematodes feeding on microflora and protozoans results in the release of excess inorganic nutrients, particularly N, that can be utilised by crops and hence they accelerate nutrient cycling in soils.

In a large survey (450 soil samples from 22 sites in the Australian grain growing regions covering seven soil orders), Linsell *et al.* (2014) found that the most influential factors affecting nematode communities were inorganic fertilisers, soil moisture, organic matter additions and tillage. Among the free-living nematodes, bacterivores are considered to be smaller with short generation times responding quickly to increases in soil bacterial populations following inputs of organic substrates or soil disturbance.

Fungivores are larger with longer generation times responsive to saprophytic fungal populations developed on plant detritus and mycorrhizal hyphae. Predatory and omnivorous nematodes are the largest in body size with long generation times that respond to increases in microbe-feeding nematodes and protozoans but are most sensitive to agronomic disruptions to the soil ecosystem. Under CA, soils receiving greater additions of organic materials are enriched with bacterivores and fungivores. At a southern Australian site, the nematode community under no-till was dominated by fungivores (reflecting residue retention on the soil surface favouring fungal decomposition) and the large omnivorous nematode (*Eudorylaimus*) indicating a more structured community due to little soil disturbance than with conventional tillage which was dominated by bacterivores (probably due to stubble incorporation) (Linsell *et al.* 2014).

Suppression of plant-parasitic nematodes General suppression of plant parasitic nematodes in a soil largely results from organic matter inputs stimulating a range of soil biota that prey on (*e.g.* predatory nematodes) and parasitise (*e.g.* bacteria and fungi) nematodes (Stirling 2014). Among the predators of nematodes are other specialised nematodes such as *Mononchus* spp., and microarthropods such as springtails and mites. Nematophagous fungi kill by colonising the nematode. In addition, zoosporic fungi and oomycetes, and bacteria parasitise nematodes. Most of these organisms are non-specific in the species of nematode that they attack, preying on or parasitising free-living as well as plant parasitic nematodes. Addition of organic matter through stubble retention increases the population sizes of saprophytic nematode-trapping fungi and predators such as microarthropods and mites, and stubble on the soil surface moderates surface soil temperature extremes and reduces evaporation, creating a better environment for organisms that prey on nematodes. A pasture phase can contribute to this process as pasture was found to support more abundant and diverse populations of nematodes, including omnivorous and predatory nematodes than adjacent cropped soil whether managed by direct drilling or conventional cultivation (Yeates and Stirling 2008).

Specific suppression on the other hand is mediated via organisms with a narrower range of nematode hosts, *e.g.* the oomycete *Nematophthora gymnophila* and the fungus *Pochonia chlamydosporia* that control cereal cyst nematode *Heterodera avenae* (Stirling 2014). Other examples of specific suppressors are the mycelial and endospore-forming bacteria *Pasteuria* spp. where *Pasteuria thornei* infects root-lesion nematodes (*Pratylenchus* spp.), and *Pasteruira penetrans* infects root-knot nematodes (*Meloidogyne* spp, Stirling 2014). Since the propagules of the biocontrol agent are most likely to be associated with the body of the dead nematodes close to old roots under no-till, roots of the new crop would likely follow old root channels where there would be a high concentration of the propagules of the nematode-attacking organisms providing better biocontrol than if these physical relationships were disrupted through soil tillage (Stirling 2014).

In the subtropical grain region of north-eastern Australia the root-lesion nematode *P. thornei* attacks a range of cereal and pulse crops growing on Vertosols (Thompson *et al.* 2008). Under conservation agriculture, nematodes can occur in the soil profile to depth (*e.g.* 60 cm), but sometimes nematode numbers are lower in the topsoil. It has been suggested that this is due to suppression of *P. thornei* in this biologically active layer (0-15 cm, Stirling 2014). An alternative hypothesis is that elevated temperatures in the topsoil over summer and faster desiccation contribute to increased death rates of *P. thornei* in the topsoil. Desiccation and heating of the topsoil are likely to be greater where stubble is burnt leaving the soil exposed to the sun: the soil is then tilled during the fallow period exposing fresh surfaces to heating and drying (Thompson *et al.* 2018).

Mesofauna – Microarthropods

Microarthropods are important intermediary members of the soil foodweb with a key role in the decomposition of crop residues and SOM, and accelerating the mineralisation of plant nutrients (*e.g.* N and P) through consumption of microbes. They can also consume spores and hyphae of pathogenic fungi and AMF, and aid in the dispersal of propagules of AMF. CA can alter the abundance and composition of springtails. For example, studies on the effects on microarthropods of three long-term treatments (*i.e.* conventional tillage/stubble burned, no-till/stubble retained, conventional tillage/stubble incorporated), in wheat cropping systems in two field experiments at Harden and Cowra in southern

NSW, indicated that springtails (33 species identified) and mites (67 species identified) had increased numbers under stubble retention (standing or incorporated) than under stubble burned, and fungal feeding species were also proportionally higher with stubble incorporation. Mites predominated during dry periods and springtails when the soil was wetter (Longstaff *et al.* 1999).

Macrofauna – Earthworms and termites

Earthworms Earthworms (Phylum Annelida) feed largely on decaying plant material (detritivores) on the soil surface and in the soil itself where they also consume microbiota including mycorrhizal fungi and accelerate mineralisation of nutrients such as N into plant available forms. The burrows (biopores) they create in the soil are significant conduits for water percolation into the soil profile. The casts (faecal pellets of ingested soil enriched with organic matter waste) that they leave on the soil surface and in their burrows contribute to better soil structure and nutrient supply. Traditional methods of burning stubble and cultivating the soil have been detrimental to earthworms. In contrast, CA provides stubble as a food base for earthworms, and reduced tillage decreases the mechanical impact on earthworms *per se* and disruption of their burrows. The combination of reduced/no-till with surface retention of stubble has meant that the topsoil remains wetter for longer and is therefore more suitable for earthworm activity.

In the southern temperate grain region, earthworms belonging to the lumbricid species *Aporrectodea caliginosa* were found to be twice as numerous in wheat cropped soil under reduced tillage compared with conventional cultivation in a red-brown earth soil (Rovira *et al.* 1987). In a long-term experiment on a Vertosol in the sub-tropical grain region, earthworms of the species *Aporrectodea trapezoides* were six times more numerous with 21 times the biomass under no-till and stubble retention than under mechanical tillage and stubble burning, 5 months after a wheat crop (Thompson 1992). *A. trapezoides* was also more efficient in recycling N from plant residues and improving wheat growth than *Aporrectodea rosea* in southern Australia (Baker 1996). Under no-till and stubble retention on a Vertosol, the deep burrowing earthworm *Polypheretima elongata* produced many tunnels and an estimated 500 t/ha of casts deposited on the soil surface in 2 years in a field experiment in a sub-tropical environment. Compared with soil, these casts were enriched in nutrients by 62% for nitrate, 29% for extractable P and 27% for organic C (Wildermuth *et al.* 1997).

Soil compaction, resulting from pressure of heavy farm machinery used when soil is wet beyond its plastic limit, can be as detrimental to earthworms as tillage. On a Vertosol in central Qld, compaction once annually reduced mean macrofauna numbers from 70 to 15/m and earthworm numbers from 41 to 2/m. The soil compacted above its plastic limit retained higher shear strength and resistance to a cone penetrometer than the non-compacted treatment for 5 years following the cessation of compaction. However, annual compaction with an axle load of 6 Mg when the soil was drier than the plastic limit in the top 0.08 m had no adverse effects on the soil macrofauna (Radford *et al.* 2001). Insufficient earthworms in the compacted treatments was attributed to the persistence of the compaction effects (Radford *et al.* 2007).

Despite obvious benefits to agriculture from earthworm activities, the greater permeability of the soil due to earthworm burrowing can result in leaching of nitrate (Subler *et al.* 1997) and in some circumstances, where large numbers of earthworms are present under CA extra N fertiliser may be required compared with conventionally cultivated treatments (Thomas *et al.* 2003).

Termites Unlike earthworms, termites do not require moist soil to move and therefore, they are active throughout the year. Ants and termites have similar functional roles to earthworms as ecosystem engineers in drier and hotter regions under low tillage and they may provide valuable ecosystem services in dryland agriculture in the Mediterranean-type and arid climates (Evans *et al.* 2011). In long-term field experiments on Vertosols cropped to sorghum and wheat in semiarid central Qld, four species of subterranean termites occurred regularly in no-till treatments but were absent from cultivated treatments (Holt *et al.* 1993). Termite galleries extended to at least 500 mm below the soil surface with significantly more gallery structures under no-till (~70% of samples), than reduced tillage (~25%) and conventional tillage (0%) (Holt *et al.* 1993). The lack of termites in the tilled treatments was considered to be due to

the physical disruption of the termite feeding galleries. More galleries were noted where stubble was retained than removed, particularly under no-till, indicating that the crop stubble was food for the termites which contributed to its rapid decomposition and release of nutrients. In a 5-year experiment, Robertson *et al.* (1994) measured significantly higher population densities of detritivores and predators in soil under no-till than under conventional cultivation and suggested that no-till increased the sustainability of the ecosystem through increasing fauna responsible for soil amelioration and predation of insect pests. Increased wheat yields with no-till compared with conventional tillage were considered to be due to greater infiltration of water into the soil via biopores created by soil fauna (Radford *et al.* 1995). In the north eastern limits of wheat production in WA, ants and termites increased wheat yield by 36% due to increased soil water infiltration and improved soil nitrogen (Evans *et al.* 2011).

Evidence for value for beneficial functions

Beneficial functions of individual and groups of microorganisms from the adoption of CA in terms of N cycling, AMF benefits to P and Zn uptake, and disease suppression in soils have been articulated above. Improvements in these functions often benefit crop productivity through better plant nutrition, crop health and maintenance of overall soil quality, especially when all the three principles of CA, *i.e.* no-till, stubble retention and crop rotation, are practised (Mezzalama *et al.* 2011, Pittelkow *et al.* 2014). In addition, there is a collective benefit from microbial communities interacting with each other under CA promoted by the combination of:

- enhanced food reserves for microbial activity and potential to increase soil biota diversity, through retention of stubbles and organic matter; and
- enhanced microbial and soil faunal activities from reduced tillage due to preserved soil structures including stable aggregates containing favourable microsites for microbial processes, and biopores created by soil fauna that are critical for the transport of organic matter, nutrients and water to depth in soil profiles.

Biopores and aggregates enable stable coexistence between microbial groups allowing cooperative microbial functions among a broad range of microorganisms responsible for nutrient capture and transformations, and plant protection. The development and maintenance of these structures is dependent on retaining spatial connectivity among soil organisms and between microbially rich microsites, which can be disrupted severely by cultivation, particularly if it is intense or repeated, as shown above for non-symbiotic N-fixation and disease suppression.

It has been demonstrated that CA results in concentration of organic matter at the soil surface in comparison with conventional cultivation. Whilst this is true in the short term, over time, transport of organic matter, nutrients and water by soil fauna down biopores, which they create, has the potential to increase organic matter at depth, creating stable environments for both microbial activity, root development and root-microbe interactions including disease suppression, and nutrient and water supply. The introduction of diverse rotations comprising plants with different root architectures and exudates is also likely to expand this process. Increases in microbial diversity and reduced proliferation of soil-borne pathogens following increases in plant diversity have already been demonstrated (Gupta *et al.* 2011, Yukicevich *et al.* 2016).

Interventions to maximise biological functions in CA

CA has increased soil biota diversity and beneficial functions in the low organic matter Australian agricultural soils that were depleted following decades of excessive cultivation and crop residue removal. Two of the key challenges for the continued use of CA are related to herbicide resistance in weeds and controlling crop diseases. The heavy reliance on herbicides to control weeds has led to herbicide resistant weeds, prompting the development of new measures including various harvest weed seed control (HWSC) strategies (see Chapters 6 and 10). Some growers are introducing occasional (strategic) tillage (Dang *et al.* 2015 and Chapter 7) or using rotations and green manuring to improve weed control. The need to develop novel weed control measures is further driven by observations that microbial processes in soils can be negatively impacted by some herbicides. For example, there is

evidence that mineralisation of N can be reduced by herbicides such as sulfonylureas (Group B) and triazines (Group C) (Rose *et al.* 2015, Gupta and Neate 1997). Motta *et al.* (2018) measured changes in the gut microbiota and increased mortality of honey bees exposed to glyphosate, which is the main knockdown herbicide in no-till systems across Australia and elsewhere and is under increasing scrutiny and risk of banning in some countries. Future multidisciplinary agronomic research could focus on increasing early crop vigour to outcompete weeds through strategic placement of nutrients below the seed at seeding combined with breeding of cultivars that produce natural herbicides and /or contain early vigour traits (see Chapter 17).

Biological disease suppression could help combat the effects of soil-borne diseases for which there are no effective chemical or plant-based control options currently available, but the time required to improve the capacity of resident soil biota for disease suppression through management practices alone makes this a challenge. Although there are no resistant varieties against soil-borne diseases, there is evidence that rhizosphere communities associated with some crop varieties reduce the susceptibility to plant pathogens (Mendes *et al.* 2017). By increasing our understanding of rhizosphere microbiology of cultivars and parents of modern varieties, it may be possible to develop new varieties with 'designer plant-microbe combinations' to improve exploitation of microbial diversity, and control diseases (Neate and Gupta 2018).

Microbial communities (microbiome) associated with roots, now considered as an extended phenotype of plants, have been shown to have a major impact on plant health through interactions on growth and development, facilitation of nutrient uptake and the ability to tolerate biotic and abiotic stresses. New molecular ('*omics*') tools are helping to identify the key drivers of diversity and functional potential of the microbiome of the plant, along with an understanding of spatial and temporal factors that operate under field conditions. This new knowledge presents an opportunity to develop designer microbiomes tailored for individual management systems and environments.

Inoculation of known beneficial microorganisms has been used for many years, and inoculation of legumes with *Rhizobium* spp. has been a successful tool for capturing atmospheric N by legumes and enhancing N availability in a range of soil types and regional environments across Australia. In more recent times, inoculants have been developed to promote plant growth and suppress plant disease (Barnett *et al.* 2019) and for P acquisition from soil (Richardson and Simpson 2011). In many instances the success of inoculation for biocontrol in the field environment has been variable due in part to problems associated with survival, in particular with rhizosphere microorganisms. However, inoculants that are endophytes, which reside within the target plant, are protected from competition from natural microflora. Despite this, not all inoculations are successful due to many biotic and abiotic factors including environmental conditions that influence plant-pathogen-microbe interactions. Inoculation into soils without a target plant has generally been less successful. For example, water repellency in sandy soils was reduced by the addition of wax-degrading bacteria under laboratory conditions but not in the field (Roper *et al*. 2015). However, by creating an environment that promoted the growth and activity of naturally-occurring wax-degrading bacteria, through adoption of CA and addition of lime to the soil, significant reductions in soil water repellency have been measured (Roper 2005).

In recent years a 'biological amendment movement' has caught the imagination of some farmers, but the success of these approaches has not been well demonstrated. These amendments range from individual and combinations of microorganisms, to biological materials. Often these biological amendments lack robust experimental trials proving their value or otherwise, and this has jaded the trust of growers in such amendments (Farrell *et al.* 2017). However, biological amendments that promote the activities of naturally-occurring microbial communities and their functions may be worth exploring. Precision agriculture may enable carefully targeted applications (*e.g.* to the rhizosphere of the plant) of such amendments to derive most benefit.

Precision agriculture, including controlled traffic, is enabling management of paddocks based on potential productivity of variable soil types and nutrient availability within the paddock. Precision sowing technology and Global Positioning System (GPS) guided seeding are increasingly common and present the opportunity for strategic placement of seed in relation to last season's crop rows, providing

benefits through water harvesting, increased nutrient availability and reduced weed seed populations. In the lower rainfall regions of southern Australia and WA under CA, surface soils on or near the previous year's row represent a rich detritusphere with enhanced microbial diversity and activity compared with inter-row soils. The down side is that on or near row locations may pose a greater soil-borne disease risk and therefore, there is likely to be a trade-off between beneficial and deleterious microbial communities (Gupta *et al.* 2018). A better understanding of spatial variation in microbiological communities and functions is needed to harness the benefits from the increased microbial diversity in CA systems. Controlled traffic is reducing the areas within paddocks exposed to wheel traffic thereby preserving soil structure and microbial interactions in the soil.

Summary

Adoption of CA in Australian cropping systems has resulted in significant shifts in soil microbial and faunal communities and functions. Much of this is beneficial and relates to the increased biologically available C which drives microbial functions such as: mineralisation of nutrients (N, P and S), including non-symbiotic N fixation; increased disease suppression in the long term; shifts in microbial communities from a bacterial dominated to a fungal dominated food web resulting in improved potential for C sequestration; conserved AMF and soil fauna communities, more stable microbial networks and functions and stable aggregates and biopores that improve soil structure and reduce soil erosion. Precision agriculture is helping to maintain these beneficial changes on more of the field by reducing compaction and conserving soil structure and biological processes on a greater proportion of the cropped area.

The negative impacts of CA in terms of increased soilborne and foliar diseases are crop and variety dependent and can be managed using diverse rotations. Likewise, new practices such as HWSC have emerged to deal with herbicide resistant weeds, thereby reducing the use and potential harm of herbicides to soil biota and functions. The tie-up of N by retained C-rich residues early in the season is short-term and readily alleviated with applied N, and in some cases may protect N from excess leaching. Some benefits are time dependent; for example, the development of microbial communities that suppress diseases may take up to 5 years and increases in C due to sequestration may take many decades. Deliberate selection of beneficial plant microbiomes through either targeted management and/or specific selection of crop genotypes has the potential to enhance the effectiveness of future developments in CA but will require a multidisciplinary systems-based approach to research.

With the current focus on security of food to feed the growing global populations, there is a need to develop innovative cropping systems that are both economically and environmentally sustainable. For example, in Australia there is a large yield gap (>50%) between what is potentially attainable with current technology and what is actually achieved (www.yieldgapaustralia.com.au) and this has been attributed to diseases and poor synchronisation of the availability of nutrients and water with the demands of the crop. Climate variability adds additional uncertainty to the efforts to reduce the yield gap and improve food production. *Harnessing the power of soil biota as part of conservation agriculture should help us reduce the yield gap.*

References

Adl SM (2003) "The ecology of soil decomposition" (CABI Publishing: Wallingford, UK)

Angus JF, Grace PR (2017) Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. *Soil Research* **55**, 435-450

Baker G (1996) The impact of earthworms on cereal yield and grain protein levels in South Eastern Australia. Final Report GRDC Project CSO134. https://grdc.com.au/research/reports/report?id=865

Barnett SJ, Ballard RA, Franco CMM (2019) Field assessment of microbial inoculants to control Rhizoctonia root rot on wheat. *Biological Control* **132**, 152-160

Beare MH, Coleman DC, Crossley Jr DA *et al*. (1995) A hierarchical approach to evaluating the significance of soil biodiversity to biogeochemical cycling. *Plant and Soil* **170**, 5-22

Coleman DC, Callaham Jr MC, Crossley Jr DA (2018) "Fundamentals of soil ecology" (Academic Press: UK)

Cook RJ (1982) Use of pathogen-suppressive soils for disease control. In (Ed. RW Schneider) "Suppressive Soils and Plant Disease" pp 51-65 (American Phytopathological Society: St Paul, Minnesota, USA)

Cook RJ (2007) Management of resident plant growth-promoting rhizobacteria with the cropping system: a review of experience in the US Pacific Northwest. *European Journal of Plant Pathology* **119**, 255-264

Cook RJ, Rovira AD (1976) The role of bacteria in the biological control of *Gaeumannomyces graminis* by suppressive soils. *Soil Biology and Biochemistry* **8**, 269-273

Dang YP, Seymour NP, Walker SR *et al*. (2015) Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: I. Drivers and implementation. *Soil and Tillage Research* **152**, 104-114

Dick R (2018) Soil health: The theory of everything (Terrestrial) or just another buzzword? *CSA News* November 2018 pp 12-17 doi:10.2134/csa2018.63.1114

Evans TA, Dawes TZ, Ward PR, Lo N (2011) Ants and termites increase crop yield in a dry climate. Nature Communications **2,** 262

Farrell M, Macdonald LM, Jenkins SN *et al*. (2017) Understanding Biological Farming Inputs. *Final report to the GRDC*, project number CSO00044 38pp

Gianinazzi S, Gollote A, Binet M-N *et al*. (2010) Agroecology: the key role of arbuscular mycorrhizas in ecosystem services. *Mycorrhiza* **20**, 519-530

Gupta VVSR, Roper MM, Kirkegaard JA, Angus JF (1994) Changes in microbial biomass and organic matter levels during the first year of modified tillage and stubble management practices on a red earth. *Australian Journal of Soil Research*. **32**, 1339-1354

Gupta VVSR, Neate SN (1997) Impact of agrochemicals on soil biota and biological processes. *Proceedings of Symposium on Synthetic organic chemicals as pollutants in the environment* (Australian Soil Science Society: South Australian branch) 17-19

Gupta VVSR, Rovira AD, Roget DK (2011) Principles and management of soil biological factors for sustainable rainfed farming systems. In (Eds. P Tow, I Cooper, I Partridge, C Birch) "Rainfed farming systems" pp 149-184 (Springer Science and Business Media)

Gupta VVSR, Penton CR, Lardner R, Tiedje J (2010) Catabolic and genetic diversity of microbial communities in Australian soils are influenced by soil type and stubble management. *Proceedings of 19th World Congress of Soil Science* Brisbane, Australia pp. 1-4 (published on DVD) www.iuss.org

Gupta VVSR, Penton CR, Kroker S *et al*. (2014) Diversity of *nif*H-harbouring bacteria and non-symbiotic N_2 fixation in Australian cropping soils. *Proceedings of 17th Australian Nitrogen Fixation Conference*, 40-41 (Australian Society for Nitrogen Fixation: Adelaide)

Gupta VVSR, Kirkegaard J, McBeath T *et al*. (2017) The effect of stubble on nitrogen tie-up and supply. GRDC Research, Ballarat, Vic. https://grdc.com.au/__data/assets/pdf_file/0019/308044/9664-GRDC-Bendigo-update-proceedings-2018-interactive.pdf

Gupta VVSR, McBeath T, Kroker, SK *et al*. (2018) How far is too far: Precision sowing drives microbiology trade-offs with soilborne diseases. *Proceedings of 10th ASDS meeting*, Adelaide pp 88-89

Hayden HL, Savin KW, Wadeson J *et al*. (2018) Comparative metatranscriptomics in disease suppressive and non-suppressive soils for *Rhizoctonia solani* AG8. *Frontiers in Microbiology* **9**, 1-19

Holt JA, Robertson LN, Radford BJ (1993) Effects of tillage and stubble residue treatments on termite activity in two central Queensland vertosols. *Australian Journal of Soil Research* **31**, 311-317

Hoyle FC, Murphy DV (2006) Seasonal changes in microbial function and diversity associated with stubble retention versus burning. *Australian Journal of Soil Research* **44**, 407-423

Hüberli D, Miyan S, Connor M, MacLeod W (2013) Identification and bioassay of disease suppressive soils in Western Australia. *Proceedings of 10th International Congress of Plant Pathology*, Beijing, China, 25-30

Ladd JN, Amato M, Li-Kai Z, Schultz JE (1994) Differential effects of rotation, plant residue and nitrogen fertilizer on microbial biomass and organic matter in an Australian Alfisol. *Soil Biology and Biochemistry* **26***,* 821-831

Linsell K, Stirling G, Stirling A *et al*. (2014) Free-living nematodes as indicators of biological soil health. GRDC Updates www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/07/free-living-nematodes-as-indicators-of-biological-soil-health

Longstaff BC, Greenslade PJM, Colloff, M *et al*. (1999) Managing soils in agriculture. The impact of soil tillage practices on soil fauna. RIRDC Publication No. 99/18 64 64 pp (RIRDC: Barton, ACT)

Mendes LW, Raaijmakers JM, de Hollander M *et al*. (2017) Influence of resistance breeding in common bean on rhizosphere microbiome composition and function. *The ISME Journal* **12**, 1-13

Mezzalama M, Govaerts B, Sayre K, Verhulst N (2011) Conservation agriculture: a solution to soil degradation and soil-borne diseases. *CGIAR SP-IPM Technical Innovation Brief* **14**, 1-2 www.spipm.cgiar.org

Motta VS, Rayman K, Moran NA (2018) Glyphosate perturbs the gut microbiota of honey bees. *PNAS* **115**, 10305-10310

Ophel-Keller K, McKay A, Hartley D *et al*. (2008) Development of a routine DNA-based testing service for soilborne diseases in Australia. *Australasian Plant Pathology* **37**, 243-253

Owen KJ, Clewett TG, Thompson JP (2010) Pre-cropping with canola decreased *Pratylenchus thornei* populations, arbuscular mycorrhizal fungi, and yield of wheat. *Crop and Pasture Science* **61**, 399-410

Peoples MB, Swan AD *et al.* (2017) Soil mineral nitrogen benefits derived from legumes and comparisons of the apparent recovery of legume or fertiliser nitrogen by wheat. *Soil Research* **55**, 600-615

Penton CR, Gupta VVSR, Tiedje JM *et al.* (2014) Fungal community structure in disease suppressive soils as assessed by 28S LSU gene sequencing. *PLoS ONE* **9**(4), e93893

Pittelkow C, Liang X, Linquist BA *et al.* (2014) Productivity limits and potentials of the principles of conservation agriculture. *Nature* **517**, 365-368

Radford BJ, Key AJ, Robertson LN, Thomas GA (1995) Conservation tillage increases soil water storage, soil animal populations, grain yield, and response to fertiliser in the semi-arid subtropics. *Australian Journal of Experimental Agriculture* **35**, 223-232

Radford BJ, Wilson-Rummenie AC, Simpson GB *et al.* (2001) Compacted soil affects soil macrofauna populations in a semi-arid environment in central Queensland. *Soil Biology and Biochemistry* **33**, 1869-1872

Radford BJ, Yule DF, McGarry D, Playford C (2007) Amelioration of soil compaction can take 5 years on a Vertisol under no till in the semi-arid subtropics. *Soil and Tillage Research* **97**, 249-255

Richardson AE, Simpson RJ (2011) Soil microorganisms mediating phosphorus availability. *Plant Physiology* **156**, 989-996

Robertson LN, Kettle BA, Simpson GB (1994) The influence of tillage practices on soil macrofauna in a semi-arid agroecosystem in northeastern Australia. *Agriculture, Ecosystems and Environment* **48**, 149-56

Roget DK, Coppi JA, Herdina, Gupta VVSR (1999) Assessment of suppression to *Rhizoctonia solani* in a range of soils across SE Australia. *Proceedings of the First Australasian Soilborne Diseases Symposium* (BSES, Brisbane, Australia) pp 129-130

Roper MM (2005) Managing soils to enhance the potential for bioremediation of water repellency. *Australian Journal of Soil Research* **43**, 803-810

Roper MM, Gupta VVSR (1995) Management practices and soil biota. *Australian Journal of Soil Research* **33**, 321-339

Roper MM, Gupta VVSR, Murphy D (2010) Tillage practices altered labile soil organic carbon and microbial function without affecting crop yields. *Australian Journal of Soil Research.* **48**, 274-285

Roper MM, Ward PR, Keulen AF, Hill JR (2013) Under no-tillage and stubble retention, soil water content and crop growth are poorly related to soil water repellency. *Soil & Tillage Research* **126**, 143-150

Roper MM, Gupta VVSR (2016) Enhancing non-symbiotic N_2 fixation in Agriculture. *The Open Agriculture Journal* **10**, 7-27

Roper MM, Davies SL, Blackwell PS *et al.* (2015) Management options for water-repellent soils in Australian dryland agriculture. *Soil Research* **53**, 786-806

Rose MR, Cavagnaro TR, Scanlan CA *et al.* (2015) Impact of herbicides on soil biology and function. *Advances in Agronomy* **136**, 133-220

Rovira AD, RJ Smettem RJ, Lee KE (1987) Effect of rotation and conservation tillage of earthworms in a red-brown earth under wheat. *Australian Journal of Agricultural Research* **38**, 829-834

Ryan MH, Kirkegaard JA (2012) The agronomic relevance of arbuscular mycorrhizas in the fertility of Australian extensive cropping systems. *Agriculture Ecosystems & Environment* **163**, 37-53

Sanderman J, Farquharson R, Baldock J (2010) Soil carbon sequestration potential: a review for Australian agriculture. *Report for Department of Climate Change and Energy Efficiency.* 80pp

Six J, Elliott ET, Paustian K (2000) Soil macroaggregate turnover and microaggregate formation: a mechanisms for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* **32**, 2099-2103

Stirling GR (2014) "Biological control of plant-parasitic nematodes: soil ecosystem management in sustainable agriculture" 2nd edn (CAB International Wallingford: UK.)

Subler S, Baranski CM, Edwards CA (1997) Earthworm additions increased short-term nitrogen availability and leaching in two grain-crop agroecosystems. *Soil Biology and Biochemistry* **29**, 413-421

Thomas GA, Thompson JP, Amos RN (2003) A long-term fallow management experiment on a Vertosol at Hermitage Research Station in southern Queensland, Australia. *Proceedings of 16th Triennial International Soil Tillage Research Conference* pp 1223-1228

Thompson JP (1987) Decline of vesicular-arbuscular mycorrhizae in long fallow disorder of field crops and its expression in phosphorus deficiency of sunflower. *Australian Journal of Agricultural Research* **38**, 847-867

Thompson JP (1992) Soil biotic and biochemical factors in a long-term tillage and stubble management experiment on a vertisol. 2. Nitrogen deficiency with zero tillage and stubble retention. *Soil and Tillage Research* **22**, 339-361

Thompson JP, Bowman R, Seymour NP *et al.* (1997) VAM boosts crop yields. The natural way to healthy crops. QDPI *Farming Systems Institute Crop Link Research Focus* 8pp (QDPI: Brisbane)

Thompson JP, Owen KJ, Stirling GR, Bell MJ (2008) Root-lesion nematodes (*Pratylenchus thornei* and *P. neglectus*): a review of recent progress in managing a significant pest of grain crops in northern Australia. *Australasian Plant Pathology* **37**, 235-242

Thompson JP, Clewett TG, Fiske ML (2013) Field inoculation with arbuscular-mycorrhizal fungi overcomes phosphorus and zinc deficiencies of linseed (*Linum usitatissimum*) in a vertisol subject to long-fallow disorder. *Plant and Soil* **371**, 117-137

Thompson JP, Rostad HE, Macdonald, B, Whish JPM (2018) Elevated temperature reduces survival of peak populations of root-lesion nematodes (*Pratylenchus thornei*) after wheat growth in a vertisol. *Biology and Fertility of Soil* **54**, 243-257

Ward PR, Roper MM, Jongepier R, Alonso Fernandez MM (2013) Consistent plant residue removal causes decrease in minimum soil water content in a Mediterranean environment. *Biologia* **68**, 1128-1131

White RG, Kirkegaard JA (2010) The distribution and abundance of wheat roots in a dense, structured subsoil-implications for water uptake. *Plant, Cell & Environment* **33**, 133-148

Wildermuth GB, Thompson JP, Robertson LN (1997) Biological change: disease, insects and beneficial organisms. In (Eds. AL Clarke and P Wylie) "Sustainable Crop Production in the Sub-tropics − An Australian Perspective" pp 112-130 (QDPI: Brisbane)

Yeates GW and Stirling GR (2008) Regional patterns among soil nematode assemblages in Australasian pastures and effects of management practices. *Australasian Plant Pathology* **37**, 298-307

Yukicevich E, Lowery T, Bowen P *et al*. (2016) Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture. A review. *Agronomy for Sustainable Development* **36**: 48-62