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Review

Potential roles of biological amendments for profitable grain production – A review

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ABSTRACT

There is increasing interest in use of 'alternative' soil amendments in agriculture, but the wide range of resources and products available differ greatly in their potential to overcome soil constraints and improve nutrient use efficiency. The three main types of biological amendments can be categorised as biostimulants, organic amendments and microbial inoculants. Many have potential to influence biological, chemical and physical conditions of soil, but most are not well researched or easily used in agriculture. The main exception is legume inoculants, which are very well researched and contribute enormously to agricultural productivity when legumes are incorporated into farming systems. Biostimulants include amino acids, chitosan, seaweed extracts and humic substances. Organic amendments include manures, composts, compost derivatives and biochars. Microbial inoculants include specific bacterial inoculants for legumes, and less specialised rhizosphere bacteria, arbuscular mycorrhizal fungi, ectomycorrhizal fungi and a range of disease suppressing microorganisms. Some biological amendments applied to soil may be more effective when used in combinations rather than singly. Furthermore, those used over longer periods may have potential for cumulative effects not captured when used over shorter timeframes. Such differences in effectiveness would occur primarily where benefits involve microbial interactions with chemical and physical soil processes leading to slow transformations within the soil matrix that influence soil fertility and soil health. Similarly, addition of manures and composts may require several years for any quantifiable increase in soil organic C. Although considerable knowledge of the modes of action of many biological amendments is available, their performance under field conditions is usually less well understood. The wide variety of natural and manufactured products available in most cases precludes adequate peer-reviewed research to support claims about their effectiveness. This can lead to proliferation of unsubstantiated assertions of efficacy. This review highlights the lack of field-scale evidence of benefits for many biological amendments with potential to be used in agriculture. We propose complementary approaches of (i) laboratory- or glasshouse-scale research to understand modes of action, and (ii) targeted field-scale participatory research involving groups of farmers using on-farm trials as a forward pathway. Use of biological amendments to overcome soil constraints is expected to expand with intensification of agriculture and as a result of climate change. Therefore, information that enables farmers to discriminate among products that have different levels of effectiveness is necessary, and on-farm participatory research should contribute to addressing this need.

1. Introduction

A wide range of resources and products is available for use in agriculture as soil amendments to overcome constraints to nutrient use efficiency and productivity. Biological amendments applied to agricultural soils include biostimulants, organic amendments, microbial inocula, and pelletised formulations and extracts such as compost teas (Quilty and Cattle, 2011; Traon et al., 2014; Yakhin et al., 2017). An important driver for continuing interest in use of biological amendments is the increasing focus on recycling of municipal wastes, industrial organic wastes, food processing wastes and sewage treatment wastes (Alvarenga et al., 2017). This encompasses reduced landfill and methane production and potential to return nutrient resources to agricultural land (Chen et al., 2016; Riggio et al., 2016). Although

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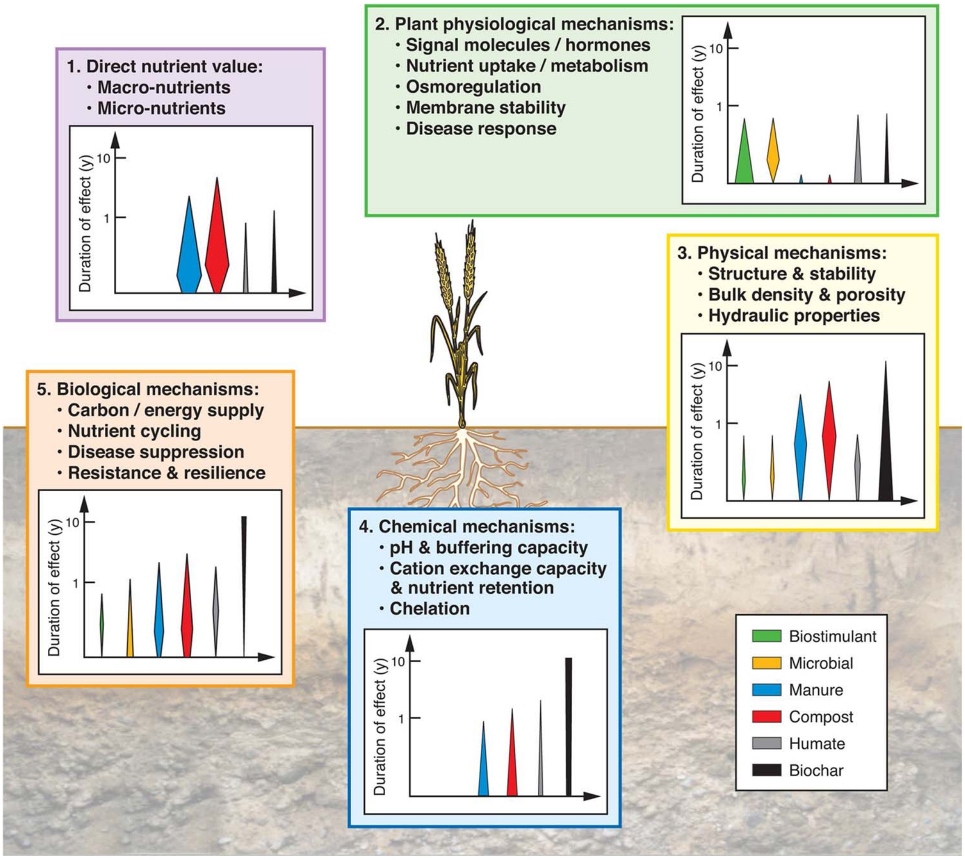

Fig. 1. Potential benefits from application of biological amendments in agriculture can be associated with direct nutrient contributions, plant physiological responses, and/or modifications in soil physical, chemical or biological components of soil health. The biological amendments are very varied but are categorised here as biostimulants (plant growth stimulants), microbial (including rhizobia for legumes and wider groups of microbial inoculants), manure and compost, humates (humic substances, some of which also fit the category of biostimulants), and biochar (includes biochars with a range of different properties). The width of bars indicates estimates of generalised intensity of response and the length of the bars indicates duration of response in years (y). Generalised effects include a range of methods of application and modes of action.

various forms of biological amendments have always been available, there are questions about their efficacy for increasing the profitability of agricultural systems (Quilty and Cattle, 2011), particularly when transport and application costs for the farmer are considered. Plant responses to biological amendments are often uncertain compared with conventional inputs used to ameliorate soil constraints to production.

As the range of biological amendments increases, it can be difficult to identify the appropriate amendments that will address local soil constraints with certainty and without introducing risks (Castán et al., 2016). Nevertheless, potential benefits from use of some biological amendments are related to direct nutrient contributions, plant physiological responses to stress, stimulation of plant growth not related to nutrition, protection against plant disease, and alterations in soil physical, chemical and biological components of soil health (Fig. 1). The magnitude and duration of any benefit will depend on the form and characteristics of the amendment, as well as the context of its application, including prevailing soil and climatic conditions.

Common soil biological constraints in agriculture include those related to low organic matter content (Hoyle et al., 2014; Aye et al., 2016). Soil C in cropped agricultural soils usually declines over time (Luo et al., 2010) unless there are significant changes in management practices, such as the inclusion of effective rotations. Soil organic matter may be augmented by application of compost or manures, with management practices that protect organic matter a high priority, but generally this is not currently a common option in rain-fed cropping.

Some biological amendments, including biostimulants, may offer the potential of improving the capacity of crops to tolerate a range of stresses. Seasonal constraints associated with moisture stresses that contribute to yield loss in crops include frost and heat-stress (Smith et al., 2009), and the amount and distribution of rainfall can lead to drought-stress (Heng et al., 2007). For example, short dry spells can occur in any season, even more frequently than droughts, and significantly affect crop yield (Rockström et al., 2010). As low and erratic rainfall and temperature extremes become more common due to climate change (IPCC, 2007), a key consideration in these environments is to lower production risk by stabilising yields.

The use of biostimulants in agriculture has been estimated to be growing at an annual rate of 12.5% (Calvo et al., 2014) with projections for considerable expansion (Yakhin et al., 2017). The resurgence in interest in use of biological soil amendments includes use of products and processes for which there is often little or no scientific research underpinning their effective use or modes of action (Edmeades, 2002; Yakhin et al., 2017). In contrast, successful inoculant industries are underpinned by extensive research and tight regulation based on well-defined industry standards (e.g. legume inoculation (Howieson and Dilworth, 2016)). Scientific knowledge that enables confirmation of claimed benefits is not often published in the peer-reviewed literature and is therefore not widely available for most marketed products. Where information is available, it may be developed through participatory on-farm research (Schut et al., 2016) or experimental field trials (Speirs et al., 2013).

Within the context of emerging expansion of use of biological amendments in agriculture, and limited levels of justified evidence for their potential benefits when used by farmers, we aim to provide an overarching view of the range of biological amendments available, with evidence of their potential to improve productivity in rain-fed agricultural systems. Our intention is to provide a framework which could be used to guide decisions around the choice of amendments based on their modes of action and how they influence underlying constraints to agricultural productivity.

2. Potential benefits from use of biological amendments

Assessment of the potential benefits of biological amendments offers a means to decide whether their use is an appropriate management option to meet farm production objectives. They may include: (i)

Table 1
Major constraints to agricultural production and examples of categories of biological amendments that have potential to be used to address these constraints.

Constraint	Biostimulant				Organic amendment						Microbial inoculants
	Chitosan	Amino Acids	Humic substances	Seaweed extracts	Animal manures	Composted amendments	Compost teas	Vermi-composts	Biochars	Biochar enhanced products	
Soil/landscape constraints											
Landscape											
Salinity					X	X		X			
Erosion			X		X	X	X	X			
Soil											
Biological											
Low organic C			X		X	X	X	X	X	X	
Low microbial biomass			X	X	X	X	X	X		X	
Low soil N			X		X	X	X	X		X	X
Chemical											
Low pH						X		X	X	X	
High pH						X		X			
Low pH buffering capacity			X			X	X	X	X	X	
Low available nutrients			X	X	X	X	X	X	X	X	X
High P sorption					X	X		X		X	X
Salinity					X	X		X			
Sodicity					X	X		X			
Low CEC			X		X	X	X	X	X	X	
Physical											
Water holding capacity	X		X		X	X	X	X	X	X	
Infiltration			X		X	X	X	X	X	X	
Compaction			X		X	X		X	X	X	
Aggregate stability	X		X		X	X	X	X			X
Plant constraints											
Disease	X		X	X		X	X	X			X
Low mycorrhizal status					X	X	X	X			X
Low nodulation/ low N_2 fixation											X
Seasonal constraints											
Drought		X	X	X		X	X	X			
Frost		X	X	X			X	X			
Heat		X	X								
Flooding			X			X			X	X	

meeting product and farming process standards to access specialised markets, (ii) decreasing or substituting use of conventional synthetic fertilisers, (iii) increasing the quantity of C sequestered in soil, (iv) using recycled C and nutrients from waste materials, and (v) addressing the lack of alternative products.

Selection of a biological amendment needs to be based on (i) site-specific soil and seasonal constraints to plant growth and soil health, and (ii) evidence that predicts which amendment(s) would overcome existing constraints or reduce the risk of developing constraints. Biostimulants, organic amendments and microbial inocula are used to overcome different soil constraints (Table 1). In addition to potential benefits, potential risks include salt accumulation, accumulation of heavy metals, unacceptable odour, threats from increasing suitability of plant pathogens to cause disease, and greenhouse gas production (e.g. nitrous oxide, Cayuela et al., 2010).

2.1. Biostimulants

Yakhin et al. (2017) conducted an extensive review of the history and diversity of biostimulants, most of which have a biological origin. Biostimulants contain substances and/or microorganisms that have potential to stimulate natural soil or plant processes leading to a range of agricultural benefits. Although they are gaining widespread attention because of their potential to improve the farm resource-base (Calvo et al., 2014; Yakhin et al., 2017), the extent to which this occurs can be open to conjecture.

The composition of biostimulants has been broadly categorised according to chemical groups such as amino acids, chitosan, seaweed extracts, humic substances and other potentially bioactive agents (Calvo et al., 2014). Other recent reviews focused on specific groups of biostimulants, such as humic substances (Rose et al., 2014), multiple aspects of major amino acids, peptides and amine-based strategies for enhancing plant adaptation and/or tolerance to environmental stresses (van Oosten et al., 2017) such as salinity (Aydin et al., 2012), drought (Zhang and Schmidt, 1999), heat (Kauffman et al., 2007), and cold (Kauffman et al., 2007; Anjum et al., 2014a), and the effects of chitosan (Hadwiger, 2013). The role of seaweed extracts in agriculture has also been reviewed (Craigie, 2011; Khan et al., 2009). Potential benefits from biostimulants (Table 1) include reduction in disease (e.g. chitosan), increased stress tolerance (e.g. amino-acid containing products), increased aggregate stability (e.g. humic substances) and increased nutrient uptake (e.g. seaweed extracts).

2.1.1. Chitosan

The main potential role of chitosan is in management of plant disease. Low concentrations of chitosan of 0.5–1.0 mg mL^{-1} applied as a seed coating and in growing media reduced the number of root lesions in tomato plants infected with *F. oxysporum* (Benhamou et al., 1994).

Evidence of disease suppression has been demonstrated in rice, wheat, oil seed rape, and grape vines (Badawy and Rabea, 2011). In wheat, applications of 2–8 mg mL^{-1} chitosan to seeds controlled seed-borne *Fusarium graminearum* infection by stimulating the production of phenolic acids by stimulating antimicrobial activity (Reddy et al., 1999). A combination of chitosan seed coatings and chitosan treated soil has been reported to be active against a wide range of plant diseases (Hadwiger, 2013). The magnitude of the benefit can be dependent on seasonal and cultural practices, thus potentially affecting the usefulness of such products compared with traditional chemical fungicides.

2.1.2. Amino acid-containing products

Amino acids and peptides have a short half-life in soil in the order of minutes to hours (Jones et al., 2009; Farrell et al., 2013), thus the efficacy of biostimulation by protein hydrolysates applied to soil is questionable and foliar application is more common. Amino acids may not be the main active ingredients in these products. For example, hydrolysates of alfalfa plants contained the plant growth regulators triacontanol (TRIA) and indole-3-acetic acid. The hydrolysate (or the equivalent amount of TRIA) increased maize biomass exposed to 25, 75 and 150 mM NaCl (Ertani et al., 2013). In another study, the effect of a suspension of the ground seeds of *Lupinus albus* L. applied as a single foliar application significantly increased seedling growth and yield of wheat by 37%. Purification and *in vitro* tests suggested that the main active ingredient was glyceryl trilinoleate or trilinolein rather than amino acids (Van der Watt and Pretorius, 2014).

Exogenously applied proline can be osmo-protective and cryo-protective to higher plant cells (Rhodes et al., 1999). A common response to salinity is the generation of reactive oxygen species that trigger oxidative stress and its regulation by antioxidants such as superoxide dismutase, catalase and peroxidases. The activity of antioxidant enzymes has been shown to increase with exogenous application of proline (Ertani et al., 2013). Exogenous proline applied to wheat grown in nutrient solution delayed wilting under osmotic stress (Rai, 2002). Under water stress, a replicated field experiment consisting of irrigation water deficit applied at vegetative, flowering or grain filling stages of corn and foliar application of unspecified types and rate of amino acids either before or after application of water deficit showed that the amino acid benefited grain yields (Kasraie et al., 2010). Here, the effect of water deficit on yield depended on the growth stage at which it occurred and similarly, the effect of application of amino acids depended on the time of application.

2.1.3. Humic substances

Understanding the chemical nature of humic substances continues to develop and in the context of biological amendments, they are complex organic macromolecules applied to soils and plants to impart a biostimulant effect (Little et al., 2014; Bulgari et al., 2015). This reflects the traditional view that humification in soil results in large macromolecules that are rendered biologically stable due to their chemical complexity (Brady and Weil, 2008). However, despite the concepts of humification and indeed humic substances themselves being long established, modern analytical techniques consistently fail to observe such predicted macromolecules (Lehmann and Kleber, 2015). Current theory suggests that the apparent recalcitrance of organic matter in soils is governed more by its interactions with the mineral matrix and inaccessibility to degrading microorganisms, than by chemical recalcitrance *per se* (Dungait et al., 2012; Cotrufo et al., 2013). As a consequence of these recent changes to understanding their chemistry, humic substances are considered to be associations dominated by hydrophobic compounds, held together by a mixture of van der Walls, π-π, and CH–π bonds (Canellas et al., 2015). These bonds can be ruptured by root exudates containing organic acids and protons. This process facilitates the uptake of humic substances and their physiological effects on plants (Calvo et al., 2014).

A variety of substrates provide sources of humic substances including lignites (brown coals), sub-bituminous coals, soil organic matter, composts, peats, and raw organic wastes (Rose et al., 2014). The humic content of a selection of six lignite or Leonardite derived products was between 14 and 82% on a dry weight basis, depending on the product and source (Yazawa et al., 2000; Little et al., 2014). Longer composting times increase the content and biological activity of the humic substances formed (Jindo et al., 2012a).

Plants grown under favourable conditions may not respond to treatment with humic substances. Lucerne and ryegrass grown under favourable glasshouse conditions (16 h day length, 23.5 °C day and 22.2 °C night temperatures and soil water content maintained at field capacity) showed inconsistent early pasture growth response to six commercial lignite or Leonardite derived products containing 14–82% humic acid and applied at the manufacturer's recommended rate. The effects varied considerably from depression of shoot growth to positive responses among treatments and soil types (Little et al., 2014).

Plant-growth responses to exogenously-applied humic substances have been reviewed by Rose et al. (2014). Products containing humic substances used in agriculture are heterogeneous in their composition and have a wide range of physico-chemical properties depending on the raw materials used, the method of extraction, and their formulation with other materials such as added plant nutrients. Because of differences in composition and multiple chemical functional groups, effects of humic substances may vary according to environmental conditions and with plant species. Effects also depend on the rate, time and location of application but these details are generally poorly described. Therefore, the extent of plant growth promotion associated with humic substances can be inconsistent and unpredictable. Based on data that included few statistically rigorous field trials testing response through to crop maturity, Rose et al. (2014) estimated an overall significant shoot dry weight increase of 22% and root dry weight increase of 21% in response to application of humic substances, but additional studies are required to substantiate the extent and consistency of positive field responses.

2.1.4. Seaweed extracts

Seaweeds have been used for many centuries either directly or in composted form as a soil amendment to improve the productivity of crops in coastal regions (Craigie, 2011). Beach-washed seaweed was the usual source, although some farmers harvested seaweeds exposed at low tide (McHugh, 2003). Seaweeds are broadly classified according to their pigmentation as brown (e.g. *Phaeophyta*), red (e.g. *Rhodophyta*) and green (e.g. *Chlorophyta*) algae. The brown algae are abundant and most commonly used as amendments in crop production systems. A considerable proportion of the 15 million tonnes of seaweed products produced annually is used as nutrient supplements and biostimulants to improve crop growth (Khan et al., 2009).

Seaweed extracts and suspensions are now more widely used in agriculture than seaweeds because they are less bulky, and easier to store, transport, dilute and apply (Khan et al., 2009; McHugh, 2003; Craigie, 2011; Arioli et al., 2015). The diversity of manufacturing processes and types of seaweed materials used result in extracts that are heterogeneous (Arioli et al., 2015). The method of preparing seaweed extracts influences their biochemical and functional properties. For example, extraction of the brown algae *Ascophyllum nodosum* at high temperature (125 °C) resulted in higher antioxidant levels compared with low temperature (< 75 °C) extracts (Guinan et al., 2013). This led to a 32-times increase in ferric reducing antioxidant power. Under high salinity (80 mM NaCl), the high temperature-derived extract added at 0.4 mL L^{-1} to nutrient solution increased lettuce yield at 21 days after transplanting by about 40%, whereas the low temperature-derived extract increased lettuce yield by about 30% (Guinan et al., 2013). In contrast, the low temperature extract applied as a 0.5 mL spray of up to 1.5% extract was more effective in reducing lesion diameter formed by both *Sclerotinia sclerotiorum* and *Alternaria brassicae* on oilseed rape leaves by about 70% compared with a 35% reduction with high temperature extract (Guinan et al., 2013).

In general, because of their potential effects against seasonal stress, benefits of seaweed extracts are likely to be seasonally dependent. For example, in broccoli, application of seaweed extract at $2\,L\,ha^{-1}$ at transplanting and two weeks later had no effect on yield of marketable products in 2011 but increased yield by 12% in 2012. In this study, the weight of individual curds increased by 6% in 2011 and 11% in 2012 (Gajc-Wolska et al., 2014). For wheat, application of a seaweed extract increased yield under K deficiency but had no significant effect on yield in treatments receiving adequate K (Khan et al., 2009).

Abiotic stresses such as drought, salinity and temperature extremes are manifested as osmotic stress and may cause secondary effects such as oxidative stress through the accumulation of reactive oxygen species, superoxide anions and hydrogen peroxide which are known to damage DNA, lipids, carbohydrates and proteins (Khan et al., 2009). Monthly field application of seaweed extract alone or in combination with humic acid increased the activity of the antioxidant superoxide dismutase by 46–180% and improved turf quality of creeping bentgrass (Zhang et al., 2003). Foliar treatment with seaweed extract of water-stressed Kentucky bluegrass raised superoxide dismutase activity and antioxidant contents which were positively correlated with plant growth parameters following (Zhang and Schmidt, 1999). In another study, application of seaweed extract to winter barley (*Hordeum vulgare* cv Igri) improved winter hardiness and frost resistance (Khan et al., 2009).

2.2. Organic amendments

Organic amendments are important sources of nutrients for sustainable agricultural production, and in combination with soil microorganisms and fauna, they can contribute significantly to improving soil structure and hence the soil environment of plants (Trivedi et al., 2017). Historically, animal manures have been used as organic amendments in agriculture, as has composted organic matter of both animal and plant origin. Use of manures and composts is less common in rain-fed agriculture and intensive horticulture than in smaller holdings. Applications of derivatives of composted materials such as vermicompost and compost teas are not commonly used in cropping systems and are attracting minor research interest. In contrast, interest in the use of biochars and products that include biochars is increasing and is attracting considerable research interest. Nevertheless, scientific evaluation of most formulations of organic amendments remains relatively limited compared with that of the use of synthetic fertilisers. The variability and complexity of soils and soil biological processes involved in transformation of organic amendments means that considerable caution is needed in generalising about their short-term and long-term effects.

2.2.1. Animal manures

Land application of manure offers a suite of soil and plant health attributes such as improvements in plant nutrient availability, soil structure, microbial activity, water holding capacity, disease suppression and soil organic matter content (O'Donnell et al., 2001; Edmeades, 2003; Jenkins et al., 2009). However, if manures are poorly managed and applied inappropriately they can have no, little or negative benefit and may result in unwanted greenhouse gas emissions, leaching and runoff (Gerber et al., 2013; Thangarajan et al., 2013). Manures vary greatly in form and chemical composition across different livestock production systems, even from one production cycle to another (Table 2), making consistent recommendations for their use problematic (Salazar et al., 2005). The extent of their benefits and risks is often variable and difficult to quantify due to heterogeneity (Ludwig et al., 2010; Ovejero et al., 2016). Some studies showed manure applications increased yields (e.g. Schröder et al., 2015) whereas other studies reported unchanged or lower yields for manure treatments when compared to synthetic fertiliser treatments (e.g. Andriamananjara et al., 2016).

Long-term use of manure can have beneficial residual effects on crop yield (Riley, 2016), even at low application rates (Conyers and Moody, 2009; Lv et al., 2011; Riley, 2016). In a comparison of 14 long-term trials in North America and Europe, manured soils were found to have higher concentrations of P, K, Ca and Mg in topsoil and nitrate N, Ca and Mg in subsoil (Edmeades, 2003). Soils amended with manure also had a greater supply of micronutrients Zn, B, Na, S and Cu (Mishra et al., 2006; Rees et al., 2014). Nevertheless, the macronutrients in manures are often unbalanced for agricultural crops and are in a dilute form making their transportation and reuse off-farm impractical and uneconomical relative to conventional micronutrient fertilisers (Edmeades, 2003; Schröder, 2005).

Manure inputs can influence the availability of plant nutrients by altering soil pH and CEC. Manures usually contain bicarbonates, organic anions and basic cations such as Ca^{2+} or Mg^{2+}, which can buffer and neutralize soil acidity (Whalen et al., 2000; Walker et al., 2004). Consequently, manured soils tend to have a higher pH, with improved fertility of acid soils by increasing the availability of N, P, K, Ca, and Mg for crop production (Whalen et al., 2000; Walker et al., 2004; Jenkins et al., 2009). Increases in soil CEC following manure application have been reported, and attributed to increases in C and soil organic matter (Gao and Chang, 1996; Miller et al., 2016). In addition to improving soil fertility, manures can also chelate heavy metals (e.g. Zn, Pb, Fe, Mn, Cu) in contaminated soils (Walker et al., 2004; Clemente et al., 2006) and improve soil properties and crop performance in saline-sodic soils (Ahmed et al., 2015).

The application of manure to soil has been shown to enhance soil structure and adsorption properties by reducing their bulk density while increasing their porosity, infiltration rate, water holding capacity, hydraulic conductivity and aggregate stability (e.g. Rasoulzadeh and Yaghoubi, 2014). In some situations, high rates of manure application may result in production of water-repellent substances by decomposer fungi and thereby reduce water infiltration (Haynes and Naidu, 1998).

Comparisons of soils under different fertiliser management systems have shown that those receiving manures had higher soil organic matter turnover and accumulate soil organic C and energy, with an enhancement of biological activity (e.g. Powlson et al., 2014). Nutrient cycling (N, P and S) can be enhanced in soils under manure management and the improved nutrient status has been linked to increased crop yield (e.g. Hopkins et al., 2011; Lv et al., 2011). Manure-amended soils can also enhance soil biodiversity in terms of species richness, abundance and functional diversity, which might explain why these soils are more resistant and resilient to stress and disturbance (Stockdale et al., 2013; Kumar et al., 2014; Larney et al., 2016; Liu et al., 2016). Soil biodiversity can be implicated in disease suppression via a variety of mechanisms including reduced abundance of certain soil fungal pathogens and pests (e.g. nematodes), release of allelochemicals, raising the pH and increasing the presence of soil microbial antagonists such as Actinobacteria (e.g. Jenkins et al., 2009; Cao et al., 2014; Heck et al., 2014; Liu et al., 2016).

2.2.2. Composts

Composting has been defined as the biological decomposition of organic matter to form a stable, humus-like end product under controlled aerobic conditions (Swan et al., 2002; Farrell and Jones, 2009a). Composts may be derived from a wide variety of organic feedstocks including agricultural wastes such as crop residues (Sparling et al., 1982), manures and litters (Liang et al., 1996; Preusch et al., 2002), and by-products such as grape marc and olive pressings (Flavel et al., 2005). Composts are also produced from urban wastes, including municipal solid waste (Richard, 1992; Farrell and Jones, 2009a,b), biosolids (Mantovi et al., 2005), and food and garden wastes (Roberts et al., 2007a; Farrell and Jones, 2010a).

Feedstock source and methods used for compost production can influence the suitability of a compost for a specific purpose (Table 3). Composts derived from feedstocks of low nutrient content such as

Table 2
Examples of chemical parameters of manures from different sources (Jenkins et al., unpublished data) DM = dry matter, MC = moisture content, EC = electrical conductivity, TC = total C, TN = total N.

Manure type	DM%	MC%	pH	EC (mS/cm)	TC%	TN%	C:N	NH_4^+ (mg/L)
Beef feedlot fresh	19.4	80.6	4.9	3.2	40.6	2.0	19.8	116
Beef feedlot mound	94.3	5.7	7.2	5.1	12.0	0.9	14.0	318
Beef feedlot stockpiled 6 months	42.9	57.1	8.6	6.2	30.1	2.4	12.4	520
Beef feedlot Stockpiled 12 months	66.7	33.3	8.5	10.7	19.5	1.3	14.9	781
Chicken meat fresh	66.7	33.3	8.9	11.0	37.6	4.9	7.7	915
Chicken meat stockpiled	52.1	47.9	8.0	10.3	40.2	3.6	11.0	402
Egg layers barn fresh	74.6	25.4	8.4	9.4	39.7	3.0	13.0	511
Egg layers barn stockpiled	56.4	43.6	7.3	8.4	30.1	4.9	6.1	345
Egg layers cage fresh	39.4	60.6	8.8	10.5	31.5	5.3	6.0	539
Egg layers cage Stockpiled	71.1	28.9	8.7	11.6	22.3	4.4	5.0	624
Pork stockpiled 3 months	47.3	52.7	8.4	10.4	38.9	2.2	17.6	876
Pork stockpiled 6 months	42.7	57.3	7.4	1.2	13.2	3.6	23.8	986
Pork stockpiled 12 months	29.0	71.0	6.4	8.1	36.8	3.3	11.0	106
Pork separated solids	26.7	73.3	7.4	3.6	39.0	2.5	15.8	213
Pork sludge fresh	35.8	64.2	7.6	7.4	44.1	5.1	8.6	520
Pork sludge aged	36.8	63.2	7.1	1.8	23.1	3.6	6.5	103
Pork semi-compost	20.4	79.6	7.6	4.6	35.4	2.1	16.8	104

municipal solid waste, or those with a risk of high heavy metal contents (biosolids, some manures) may only be suitable for remediation work. At the other end of the spectrum, nutrient-rich composts from source-separated garden and food waste are of high market value and are commonly sold at retail or to the market-garden/horticulture market (Roberts et al., 2007b; Atiyeh et al., 2001; Farrell and Jones, 2010a). Between these two extremes, there is potential for composts from urban areas to play a greater role in improving soil structure, fertility and health in agriculture.

Composts contain a range of micro- and macronutrients and influence soil chemical and physical properties including pH, CEC, porosity and water holding capacity (Bulluck et al., 2002). They can have a strong pH buffering capacity and liming effect (Farrell et al., 2011) that can increase the pH of acid sulphate soils by 4–4.5 pH units when applied at high (40% v/v) rates (Farrell and Jones, 2010b). In an agronomic setting, Bulluck et al. (2002) reported increases in pH of one unit in response to compost addition (up to 100 t ha^{-1}) over the course of two growing seasons in a series of plots in which melons, tomatoes or corn were grown in Virginia and Maryland, USA. In the same study, a 33% increase in CEC was observed in the compost-amended treatments relative to plots receiving synthetic fertiliser, and this was positively related to the increase in soil organic matter was also observed for compost-amendment treatments. In another study, no such increases in CEC (Zebarth et al., 1999), with only minor increases in CEC observed after very high rates of application of a range of composted materials. Zebarth et al. (1999) observed improvements in water retention in the loamy sand used in their study in British Colombia, Canada. In both studies mentioned above, soil bulk density was significantly reduced with application of compost (Bulluck et al., 2002; Zebarth et al., 1999).

A major factor limiting the use of composts derived from urban wastes in rain-fed agriculture is the cost of transport. While this may preclude the use of urban composts as a soil improver in more remote rural areas, many rural regions have manure-intensive agricultural enterprises such as cattle feedlots or poultry sheds neighbouring farms. Between July 2014 and June 2015, 521,000 t of composts were applied to 262,000 ha of Australian agricultural land. Although statistics on the use of composts in agriculture from the USA are difficult to obtain, a report by Platt et al. (2014) found that over 19 million tonnes of organic urban waste was diverted to composting facilities in 2012, clearly demonstrating the scale of the resource available.

Well-matured composts contain highly active microbial communities (Chander and Joergensen, 2002). When added to soil, composts can stimulate soil biota and change the microbial community structure (Cytryn et al., 2011; Bedi et al., 2009). This can alter the function of microorganisms involved in biogeochemical cycling, disease suppression and plant growth promotion, and increase nutrient availability, fertiliser use efficiency and plant growth (Fuchs et al., 2008; Bareja et al., 2010; Farrell et al., 2010; Quilty and Cattle, 2011). There are

Table 3
Examples of chemical parameters for composts produced from different organic materials.

Composted materials	pH	EC	C:N	C	N	P	K	Ca	Mg	Na	Fe	Mn	Cu	Zn	Ni	References
		ds m^{-1}		g kg^{-1}								mg kg^{-1}				
Green waste	9.0		27	167	6	0.1										Bareja et al. (2010)
	7.9	2.3											63	369	20	Farrell and Jones (2009a)
	8.1	0.7	21	132	6	2.8	7.0	2		1.1			66	56	31	Farrell and Jones (2010b)
			17	206	12	3.8	4.0	22	2.9	1.6	14.3		85	190		Quilty and Cattle (2011)
Food waste mix			15	255	17	0.2	5.0	0.0	0.1	0.6	0.2	2.8	1	2.9		Quilty and Cattle (2011)
	8.1	1.4	16.0	219	14	5.9	11.0	7.8		2.5			37	55	18	Farrell and Jones (2010b)
Municipal waste	8.1	1.1											276	213	37	Farrell and Jones (2009a)
			16	176	11	2.8	3.4									Farrell and Jones (2009b)
	7.3	3.6	25	246	10	0.9	10.1	59		8.3			329	505	87	Farrell and Jones (2010b)
	7.4	6.2	13	185	14	4.4	4.3					252	362	396		Pérez-de-Mora et al. (2007)
			10	195	19	6.5	6.7	65	4.5	5.5	5.9	840	80	184		Quilty and Cattle (2011)
Biosolids mix	7.1		9	262	29.5	14.3	11.1			3.1						Mantovi et al. (2005)
	7.6	1.8	18	193	11									122		Farrell et al. (2010)
	6.9	2.9	15	195	13	12.4	9.3					257	121	258		Pérez-de-Mora et al. (2007)
Manure mix	7.2		12	300	25											Farrell and Jones (2009b)
			12	238	20	5.8	3.9	16	4.3	0.3	7.3	684	25	302		Quilty and Cattle (2011)

Table 4
Examples of chemical parameters for 14 vermicomposts.

	pH	EC	C:N	C	N	P	K	Ca	Mg	Na	Fe	Mn	Cu	Zn	Ni	References
		ds m^{-1}		g kg^{-1}								mg kg^{-1}				
Vermicomposts	8.4	0.9	7.8	194	25	7.7	13		31	2.0	12	445	63	191	22	Nogales et al. (1999)
	8.0	1.2	7.1	205	29	7.5	7.3		31	2.5	12	378	91	237	29	
	8.0	1.1	5.8	168	29	7.3	6.7		31	2.0	13	398	89	229	28	
	8.0	1.1	9.2	202	22	7.5	5.3		27	2.3	12	390	85	232	26	
	7.4	0.6	11.5	126	11	5.6	0.3	4	1	0.1	93	83	3.1	32		Mekonnen and Argaw (2015)
	7.3	0.7	11.6	162	14	5.7	0.4	4	1	0.1	91	84	3.8	31		
	7.6	3.2		19										41	10	Mahmoud and Ibrahim (2012)
	5.9	3.2	11.6	273	24	45	4	86	5		8					Atiyeh et al. (2001)
			6.6	186	28			5			1		33	26		Quilty and Cattle (2011)
			15.0	195	13	27	92		44	0.8			50			
			17.2	172	10	27	92		45	1.0			47			
					47	2.2	15	1		0.7						
					47	1	26	2		4.4						
	6.7	3.2			12	2.6	10	36	6.1		15		5	330		Roberts et al.(2007a)

many examples of research investigating the incidence of plant diseases where composts have been supplied. While the majority of this research has been carried out in the horticultural sector (Litterick et al., 2004), there is evidence that composts may suppress crop disease in farming systems (Reddy, 2016). Fungal disease suppression (Bailey and Lazarovits, 2003) is particularly widespread in horticulture following the application of compost to soil (Scheuerell and Mahaffee, 2002).

2.2.3. Vermicomposts

Vermicompost is produced when organic material is passed through the gut of earthworms in worm farms (Domínguez, 2004); commercial and environmental interests have addressed vermicompost as a potential waste management strategy (Sharma and Garg, 2018). The chemical compositions of a number of vermicomposts are presented in Table 4. Compared to conventionally-produced thermophilic composts, vermicomposts typically contain higher nutrient concentrations (Tognetti et al., 2005). Although vermicomposts can be produced from many feedstocks, careful management of feedstock blends is needed to minimise worm mortality and maximise product quality (Nogales et al., 1999). Generally, more readily decomposable feedstocks such as food waste or manures are used for the production of vermicomposts, but successful vermicomposting of shredded woody waste was demonstrated when vermicomposted in combination with waste from khat (*Catha edulis*) leaf production (Mekonnen and Argaw, 2015).

In the context of grain production, little research has been carried out to understand the potential for vermicompost utilisation. In a bioassay experiment, vermicomposts imparted less salt stress than conventional composts or equivalent conventional fertiliser while increasing wheat growth in (Chaoui et al., 2003). There has been a particular focus on the use of vermicomposts in cereal production in India, with field studies exhibiting increased soil organic matter and wheat yield (Shukla et al., 2013) and increased pearl millet yield (Sharma et al., 2012). Both of these studies also included microbial inocula as part of the vermicompost treatment, and the vermicompost-only treatment yielded less than the microbial-vermicompost treatments. Mahmoud and Ibrahim (2012) observed that when mixed with biosolids, vermicompost both improved the yield of barley and reduced salt stress in a saline sodic soil from Egypt, indicating potential amelioration properties for degraded soils.

2.2.4. Compost teas

Compost teas are liquid extracts derived from composts (Quilty and Cattle, 2011) that are used as a soil drench, applied to the seed at sowing, or sprayed during the growing season. They are prepared from a range of materials and recipes and are used to a limited extent in small-scale cropping in foliar sprays. Preparation of compost teas is likely to be highly variable depending on the source of the composted organic matter used and the preparation technique (i.e. liquid to compost ratio and duration of incubation). Organic agricultural practices include a range of formulas for sprays prepared from composted manure, herbal preparations and composted organic matter. As with bulk composts, compost teas have been mostly researched in the high-value horticulture industry (Litterick et al., 2004; Welke, 2004) or viticulture (Evans et al., 2013), where mixed results have been noted. There have been few studies in cropping systems, although positive effects on growth or reduced fertiliser requirement were reported in a study focussing on early stages of plant growth (Reeve et al., 2010). Compost teas have been claimed to have several benefits, including reduced incidence of disease, improved soil and plant health, increased root growth and penetration, and reduced pesticide requirements (Scheuerell and Mahaffee, 2002; Pane et al., 2014). Compost tea was shown to suppress two fungi forming powdery mildew on grapevine leaves and fruit which differed in their in epidemiology (Evans et al., 2013). The ease of use of compost teas compared to compost is considerable, and if supplied as a concentrate, there would be much lower shipping costs for compost teas relative to bulk compost. This is particularly pertinent for farming operations located at great distances from either a compost supplier or a suitable source of organic waste for producing compost on-farm.

2.2.5. Biochars

Biochar is a porous, charcoal-like, material that results from thermal conversion of organic biomass (feedstock) during bioenergy processes (e.g. pyrolysis). There has been wide interest in using biochar as a soil amendment to improve soil fertility (Atkinson et al., 2010; Scott et al., 2014) and soil biology while also contributing to long-term C sequestration and greenhouse gas mitigation. Biochar producers tend to make broad claims of improved soil health and biological activity, nutrient and water retention, drainage, pH, root growth, and resistance to fungal disease. Biochar products are often aimed at the garden and horticultural markets. The scientific literature provides mixed evidence of success in their use in agriculture. A sound mechanistic understanding of how biochar can be best used to support soil health and plant productivity remains limited (Macdonald et al., 2016). Although the direct application of biochar to soil has been widely studied, there has been a recent shift towards the incorporation of biochar into a wider range of amendments including mineral fertilisers, composts and inocula.

Biochar can be produced from a wide range of organic biomasses (feedstocks), of various particle size, and under a range of pyrolysis conditions (temperature, heating rate, pressure, residence time). Consequently the variation in biochar yield, physical structure, chemical composition, and behaviour of biochars is considerable and often

Table 5
Indicative chemical parameters associated with biochars produced from different feedstocks at lower (400–500 °C) and higher (600–750 °C) temperatures by slow pyrolysis. Data represent mean values derived from UC Davis biochar database (07.02.2017) collating available literature.

Feedstock	Pyrolysis conditions	Ash	C	N	P	Ca	Mg	K	pH	EC	Surface area
		%	mg kg^{-1}							dS m^{-1}	m^2
Hardwood	400–500 °C	4.4	645	4.6	1.2	9.2	1.1	6.5	8.1	2.4	59
	600–750 °C	4.6	758	4.1	0.9	5.2	1.3	2.4	9.8	2.4	307
Manure	400–500 °C	48.7		20.1	38.0	45.5	12.5	27.0	10.2	0.8	22
	600–750 °C	52.8		16.5	61.0	60.0	33.0	28.0	10.8		42
Grass	400–500 °C	12.1	469	7.6	3.4	5.6	2.2	20.7	9.3	2.7	33
	600–750 °C	13.2	759	5.4	5.5	9.9	3.5	65.6	9.95	1.3	139

confusing. Comparing the properties of biochars between studies can be difficult, not only due to production and feedstock differences, but in association with differences in post-production treatment, particle size and the analytical methods used. Nevertheless, some generalisations can be made, and are useful in broad comparisons and in understanding the impacts reported in the literature. Some of the key parameters of biochar produced from woody, grass, and manure feedstocks differ according to high (> 500 °C) and low (< 500 °C) pyrolysis temperatures (Table 5). In general, biochars produced at higher temperatures have higher C and mineral contents, higher pH and larger surface areas; hardwood biochars tend to be richer in C and lower in nutrient content and pH; manure biochars are lower in C and higher in nutrient content, often with high amounts of calcium.

The physical structure of biochar is more friable compared to other organic amendments, with the porous structure conferring a relatively low bulk density (< 0.5 g cm^{-3}). When applied to clay-rich soils, biochar can decrease bulk density and tensile strength, potentially improving the physical environment for plant root growth (Chan et al., 2007; Atkinson et al., 2010).

Biochar pore structures are heterogeneous ranging from the micro- to macro- scales, and often resemble the original cell structure, with larger cracks resulting from the pressures and strains of thermal conversion (Downie et al., 2009). The micropore (< 2 nm) volume has been shown to correlate with the specific surface area (Downie et al., 2009), which is comparable to that of various clays (5–750 m^2 g^{-1}; Troeh and Thompson, 2005) and commercial grade activated C (300–1300 m^2 g^{-1}; Macdonald et al., 2016). Higher surface areas (> 800 m^2 g^{-1}) are associated with higher temperature biochars made from plant materials with complex cell structure. Consequently, in sandy soils where surface area is low and pore space high, biochar has been predicted to have similar effects to increasing clay content including improved water retention, microbial biomass, and protection from desiccation and microbial predation/grazing (Juma, 1993; Thies and Rillig, 2009).

Despite discussion on a range of application approaches (deep banding below the seed, incorporation with manures, composts, or slurries (Blackwell et al., 2009)), the majority of trials to date have typically broadcast applied and incorporated at 10 cm depth biochar at high rates (usually between 5 Mg ha^{-1} and > 20 Mg ha^{-1}), in combination with either a regional recommendation or half rate application of mineral fertilisers. These high biochar application rates present considerable practical and economic challenges that cannot currently be balanced with certainty in productivity gains. A smaller number of trials have tested beneath the seed banding at significantly lower rates of application (< 200 kg ha^{-1}; Blackwell et al., 2010; Farrell et al., 2014), finding only limited effects of biochar on crop yield.

2.2.6. Combinations of biological amendments

There is potential for combinations of biological amendments to achieve synergistic responses. For example, following the proposal of Dias et al. (2010) that the porous, stable, physical structure of biochar could add value to compost as a bulking agent, there has been a number of studies combining biochar with compost both during the composting phase (Prost et al., 2013) and in post-compost blending (Jindo et al., 2012b; Phuong-Thi et al., 2013). An amendment with a diverse range of organic components is likely to offer a wider range of biological, chemical, and physical functions to soil. More labile C and nutrient pools will contribute to biological activity over the immediate-to-medium term timescales, while more recalcitrant biochar pool adds physical and chemical properties that persist in the longer term. The range of reported benefits for composting includes accelerated decomposition, increased composting temperature, altered organic matter composition, reduced N loss, and pH buffering. Wood based biochars may be more suited to enhancing composting owing to higher aromatic, sorptive, and humification properties compared to rice-husk or bamboo biochars (Zhang et al., 2014).

The sorptive capacity of biochars perhaps offers some of the greatest potential in developing value-added opportunities in combination with other soil amendments. Biochars are reported to sorb a wide variety of compounds including N, P (Chintala et al., 2014), organic compounds and metals (Macdonald et al., 2016). The sorptive capabilities of high temperature wood biochar can be comparable to commercial grade activated C (Jung et al., 2013) offering potential to develop slow release, C enhanced fertilisers. The potential of charcoal (Khan et al., 2008), and more recently biochar (Kim et al., 2014), to slow the release of NPK fertiliser has been reported. Field-testing of an enhanced biochar fertiliser product in Australia has demonstrated a clear impact on the structure of the soil microbial community (e.g. co-occurrence of Acidobacteria and Verrucomicrobia (Nielsen et al., 2014)). These trials also reported a comparable yield of sweetcorn with that obtained under traditional approaches despite lower nutrient additions, suggesting improved nutrient use efficiency.

Beyond the benefits to composting and slow release style fertilisers, novel uses of biochar to capture and re-use organic nutrients from the animal sector and re-use them as biofertilisers have been proposed (Jensen, 2013). For example, based on batch sorption experiments, the use of a biochar sorbent within California's dairy wastewater management has the potential for annual capture of upwards of 12,000 t of ammonium-N and 1000 t of phosphate, providing a valuable C rich nutrient source for return to soil (Ghezzehei et al., 2014). In similar work, Yao et al. (2011) suggest that nano-sized MgO particles on the surface of a biochar (sugar-beet) are responsible for phosphorus sorption. Chemically engineering charcoal-like materials to enhance the sorption/desorption characteristics of specific compounds is an active area of materials sciences that may offer potential for the development of purpose specific biochars. However, engineering to this level would clearly add to end product costs.

2.3. Microbial inoculants

The microbial inoculant industry has a long history, with most success arising from legume nodulation (Howieson and Dilworth, 2016). Successful formulation of commercial inocula of legume root nodule bacteria depends on understanding the plant and bacterial ecology in the soil to be inoculated (Howieson et al., 1988; Howieson and Ewing, 1989). Among other microbial inoculants developed commercially, most are less robust than those developed for legumes, except perhaps the development of inocula of *Bacillus thuringiensis* (Sansinenea, 2012). Microbial inoculants may include single organisms or multiples of the same or different groups of organisms (Owen et al., 2015).

A major reason for the success of the legume inoculation industry includes (i) specificity between the bacterial and plant (Remigi et al., 2016) and (ii) very few bacteria need to survive to form effective nodules. These two attributes of the legume-bacteria symbiosis contrast with less specific associations such as those of rhizosphere bacteria (e.g. plant growth promoting rhizobacteria (PGPRs)) and arbuscular mycorrhizal fungi. For mycorrhizal fungi, multiplication and spread needs to occur both within roots during the plant growth cycle and in the soil. Similarly, rhizosphere bacteria need to multiply and survive in soil and/or on roots in sufficient numbers to have an influence. Hence, the hurdles required to establish effective inoculants of rhizosphere bacteria or arbuscular mycorrhizal fungi are far greater than those encountered for rhizobia. Nevertheless, maintenance of soil conditions that can support survival and function of all inoculants is required. Selection and quality control of inoculants is also essential (Decker et al., 2011).

2.3.1. Legume root nodule bacteria

Inoculation of legumes with their appropriate root nodule bacteria has demonstrated the benefits of including legumes in agricultural rotations (Howieson and Dilworth, 2016). Bacterial inoculants for legumes are selected for specific purposes in sophisticated inoculation programs (e.g. Howieson, 1995). They usually have a limited range in host plant specificity (Sprent, 2007). Processes for selection of inoculants for plant-specific function such as symbiotic nitrogen fixation (Batista et al., 2015) have been systematically developed based on in-depth knowledge of both plant and soil constraints (Peoples et al., 2001; Unkovich et al., 2010), inoculant production systems (Decker et al., 2004) and agricultural management practices. Quality control in the rhizobial inoculant industry is essential and well regulated (Decker et al., 2004; Decker et al., 2011).

2.3.2. Plant growth promoting rhizobacteria (PGPRs) and generalist microbial inoculants

There is a range of potential benefits from introducing microbial inoculants into soil either singly or in mixtures (Table 1). In particular, there have been extensive investigations of plant growth promoting rhizobacteria (PGPRs) (Singh et al., 2011) including species such as *Azospirillum*, *Bacillus*, *Pseudomonas* and *Providencia* added as single microbial inocula (e.g. Hungaria et al., 2010; Mader et al., 2011; Rana et al., 2012), or as mixed microbial inocula (e.g. in combination with arbuscular mycorrhizal fungi (Roesti et al., 2006)). Overall, the introduction of PGPRs into soil for improved crop production has been less effective than has the sustained success of inoculation of legumes with rhizobia in crop and pasture systems.

Rhizosphere inoculants (e.g. PGPRs) include those with either broad base targets or specific targets (Rana et al., 2012). In all cases, an understanding of the life cycles of the inoculants and their responses to a range of possible environmental conditions following inoculation onto roots or into soil is essential for predicting their usefulness. Inoculants used for disease suppression can have a wider host range (e.g. *Bacillus thuringiensis* (Sansinenea, 2012)). Similarly, the benefits of phosphate solubilising organisms are not crop-specific (Richardson et al., 2009) and if used as inoculants would have a wide host plant range.

Generalist inoculants include a variety of mixed microbial consortia or 'biofertilisers' (Kennedy et al., 2008; Rana et al., 2012) that have potential to contribute across a range of crops. These inocula may differ in the extent to which they contain organisms that are not known to be abundant in agricultural soils. An understanding of the life cycles of microorganisms is essential for determining their likely success, survival or persistence in the field. Soil constraints that interfere with some phases of the life cycles of microorganisms could lead to variability in effectiveness and override opportunity for benefits. In contrast to rhizobial inoculants, 'biofertiliser' inoculants are less well regulated (Malusa and Vassilev, 2014), and this could be problematic for consistency in their efficacy.

Selection and commercial production of some generalist microbial inoculants (e.g. *Bacillus thuringiensis*) are made for wide geographical application, especially when targeting disease or root stimulation. In situations where mixed inocula are used, selection from local soils might be a more successful approach. Another factor to consider is whether the inoculant microorganisms are to be inoculated with each planting, or whether they are required to persist in the soil between crops. In each case, different criteria for selection of microorganisms would be required. This is because inoculant criteria related to persistence may not be so important if the objective is to stimulate early seedling growth. Persistence would be important if the objective is to maintain disease protection throughout the life cycle of the plan, or during crop rotations. In all cases, the selection of inoculants needs to be closely considered in relation to other management practices, including nutrient management, which influence root growth and disease cycles.

2.3.3. Arbuscular mycorrhizal fungi

There is increasing commercial interest in use of inoculant arbuscular mycorrhizal fungi. These are generalist inoculants because they colonise roots of most plant species and there is little evidence of host specificity (Smith and Read, 2008) except when associated with ecological events (McGonigle and Fitter, 1990). This leads to more difficulties for their use as biological amendments than for specific inoculants such as rhizobia. Generalist inoculants need to tolerate a wide range of conditions, both in soil and inside roots (Abbott et al., 1992). Caution is required in selecting arbuscular mycorrhizal fungi for commercial propagation to avoid less effective taxa that may have 'weedy' characteristics (Schwartz et al., 2006) or if there is potential for other risks following inoculation (Hart et al., 2017).

There are many examples of successful inoculation with selected arbuscular mycorrhizal fungi, but the majority of studies have been conducted under controlled conditions and may not reflect field situations (e.g. Gazey et al., 2004). Furthermore, the likelihood of persistence of inoculant arbuscular mycorrhizal fungi in field soils will be relatively low if the fungi are unable to compete with those already present. Introduction of exotic arbuscular mycorrhizal fungi may have little impact in soils where their low abundance is associated with soil constraints. The abundance and effectiveness of communities of arbuscular mycorrhizal fungi are influenced by existing soil conditions and agricultural management practices, including use of fertiliser and crop rotation (Thompson et al., 2013). It is therefore necessary to have a clear understanding of the reason for low levels of arbuscular mycorrhizal fungi at any point in the production cycle before considering inoculation (Hart et al., 2017).

3. Modes of action of biological amendments

Biological amendments have been reported to influence the plant-soil system in a number of ways. They can be broadly narrowed down to four main modes of action: biological, chemical and physical effects on soil, and effects on plant physiology, including plant nutrition (Fig. 1). Many biological amendments have several potential modes of action and separation of these modes of action, both direct and indirect, is not always simple because of their interdependence on soil processes. Nevertheless, an underlying connection is often associated with soil biology with close links to soil chemical and physical processes related to soil fertility (Abbott and Murphy, 2003).

The choice of any biological amendment for use in agriculture needs

Table 6
Examples of mode(s) of action for a range of biological amendments (AAs amino acids).

Mode of action		Humic substances	Hydrolysates & AAs	Seaweed derived	Chitosan	Animal manures	Composts	Vermicomposts	Compost teas	Wood-based biochar	Manure-based biochar
DIRECT NUTRIENT VALUE											
	macro			X		X	X	X			X
	micro			X		X	X				X
PLANT PHYSIOLOGICAL RESPONSES											
	signal molecules/hormones	X	X	X	X			X	X		
	nutrient uptake metabolism	X	X	X							
	osmoregulation	X	X	X				X			
	plant disease responses			X	X	X	X	X	X		
SOIL QUALITY											
Physical	structure and stability					X	X				
	bulk density and porosity					X	X			X	
	hydraulic properties					X	X				
Chemical	pH buffering					X	X				X
	cation exchange capacity					X	X			X	X
	chelation	X		X		?	?				X
Biological	carbon/energy supply		X			X	X	X			
	nutrient cycling	X				X	X	X		X	X
	disease suppression	X				X	X	X	X	X	
	resistance and resilience	X				X	X	X	X	X	
Dominant Form:											
S = solid; G = granule/prill; L = liquid		*SGL*	*L*	*L*	*L*	*S*	*S*	*S*	*L*	*S*	*S*
Application:											
L = Land/soil; F = foliar spray; S = seed;		*LFS*	*FS*	*LFS*	*FS*	*L*	*L*	*L*	*LFS*	*L*	*L*

to be based on its mode(s) of action in relation to the specific local constraints that it has potential to alleviate. Biostimulants, organic amendments and microbial inoculants differ in their mode(s) of action and in the likely duration of their effectiveness (Fig. 1), as well as in their potential to influence at landscape, soil, plant or seasonal scales. The specific mechanisms that enable biological amendments to contribute to plant nutrition, plant physiology, plant disease reduction and soil quality are diverse (Table 6). The following section highlights modes of action that can be attributed to particular amendments. Information such as this can assist growers, agronomists, and consultants to interpret the claimed benefits of individual products. This will contribute to decision-making that includes knowledge of the major environmental constraints to production in specific scenarios (e.g. interactions between soil type, environmental conditions and plant rotation sequence).

3.1. Biological mechanisms

Biological amendments have the potential to manipulate microbial and faunal communities and the services they provide in soil in a number of ways leading to plant benefits, but some benefit plants independently of the soil processes (Table 7). The soil communities influenced by biological amendments contribute to ecosystem services including C and nutrient cycling, biological supply of nutrients and disease suppression (Bailey and Lazarovits, 2003; Cytryn et al., 2011; Johnston, 1986; Lazarovits et al., 2000; O'Donnell et al., 2001, 2007; Ojeda et al., 2010; Young and Crawford, 2004). Where plant growth is constrained in soils by low nutrient availability, there is a possibility that crop growth or yield may be improved by applying biological amendments if they are able to overcome, at least partially, the nutrient constraint.

Manures, composts and other biological amendments possess a suite of soil and plant health attributes. The soil and plant health effects of biological amendments include improved soil water holding capacity, suppression of fungal disease and increased soil C storage (Quilty and Cattle, 2011). Although the mechanisms and modes of actions are not all fully understood, biological amendments are known to interact with microbial communities in soil in a number of ways. They may stimulate microbial growth either directly by providing energy or nutrients or indirectly by increasing plant growth and enhancing root C flow (Buyanovsky and Wagner, 1986) leading to an increase in the size of the microbial biomass (Kemmitt et al., 2008). The quality and quantity of the biological amendment can further alter the biota and microbial community diversity and function (Kemmitt et al., 2008; O'Donnell et al., 2001).

Soil microbial abundance responds to addition of organic matter such as compost and manure to soil, and some of these microorganisms secrete polysaccharides or form mycelia that help bind soil particles and improve soil structure (Six and Paustian, 2014; Tisdall and Oades, 1982; Young and Crawford, 2004). This can increase water availability (Caesar-TonThat et al., 2007) and protect soil C (Dungait et al., 2012). Even if the changes are temporary, the influence may still be beneficial (Shrestha et al., 2015). Manures can promote the activities of naturally occurring soil microbial antagonists against fungal pathogens (Bailey and Lazarovits, 2003) and improve plant nutrition allowing the plant to better resist attack and induce resistance (Yogev et al., 2010). Composts and manures may also increase the abundance of bacteria that exude siderophores that bind Fe and induce deficiency in pathogenic fungal species (Leong and Neilands, 1981). However, mechanisms that reduce the soil fungal biomass may result from competitive exclusion due to differences in growth rate or to presence of inhibitory molecules (e.g. secondary metabolites or lytic enzymes) remain largely unknown. Increased colonisation of roots by arbuscular mycorrhizal fungi can occur in crops receiving manure and compost (Cavagnaro, 2015). Furthermore, arbuscular mycorrhizal fungi can increase a plant's ability to take up water and nutrients by increasing the effective root surface area for absorption (Smith and Read, 2008). Manure inputs can also increase the activities of soil fauna (including earthworms) that in turn promote better soil structure by improving aggregation and aggregate stability (van Vliet and Hendrix, 2003; Rillig and Mummey, 2006).

Given the importance of microorganisms in building and maintaining fertile and productive soils (Grandy and Neff, 2008), understanding whether and how categories of biological amendments change microbial communities should provide insights into their potential use for sustainable production. The advent of next generation sequencing methods for characterizing and quantifying microbial community structure and function enhances opportunities for identifying soil organisms, their mode of action and mechanisms involved. Elucidating the link between biological amendments and soil microbial activity offers the possibility of manipulating the size, activity and diversity of beneficial soil biota (Jenkins et al., 2009, 2010; Kemmitt et al., 2008; O'Donnell et al., 2001). However, soils are complex with multi-component interactions so understanding why they respond and how their responses can be bioengineered in a systematic and predictive way remain a significant challenges.

The modes of action of targeted inoculants (Kennedy, 2001) include direct contributions to nutrient supply, such as symbiotic nitrogen fixation (Howieson and Ballard, 2004) and phosphorus transformations (Richardson et al., 2009; Huang et al., 2017), and interference with establishment of microorganisms on plant surfaces leading to a reduction in plant disease (Evans et al., 2013) (Table 7). In contrast, the modes of action of generalist inoculants include disease suppression, root growth stimulation, and usually have a theoretical basis suggested from controlled experimental conditions with limited demonstration of efficacy under field conditions (Table 7). There is a possibility that some amendments, such as vermicomposts, may be able to benefit yield

Table 7
Examples of potential benefits and modes of action of introduced microorganisms (after Malusa and Vassilev, 2014).

Organisms	Crop Benefit	Examples ofModes of Action
Examples of 'single organism' introductions		
Root nodule bacteria *(e.g. rhizobia)*	Nitrogen supply	N_2 fixation
Phosphate solubilising bacteria	Phosphorus supply	P solubilisation
Bacterial inoculants *(e.g. Bacillus thuringiensis)*	Reduced disease	Interference with disease cycle
PGPRs[a]	Increased shoot and/or root growth	Hormone production, suppression of colonisation of roots by pathogens, synergies with other soil microorganisms in nutrient transformations
Arbuscular mycorrhizal fungi	Increased P uptake/ improved soil structure	Role of hyphae accessing P, stimulation of hyphal growth in soil leading to improved soil aggregation
Examples of 'multiple microorganism' introductions		
Consortia of microorganisms may include PGPRs, arbuscular mycorrhizal fungi, rhizobia	Increased shoot and/or root growth Reduced root disease Resilience to insect attack	Combinations of the actions above

[a] PGPRs: Plant growth promoting rhizobacteria.

and quality beyond their intrinsic nutrient content through the provision of biostimulant or hormonal compounds, as well via manipulation of the soil microbial community but this requires investigation.

3.2. Chemical mechanisms

There are two main chemical mechanisms by which biological amendments operate in order to achieve the potential positive outcomes marketed. First, there may be direct fertiliser effects, and second, the chemical properties of soil may be altered leading to a direct or indirect effect on nutrient availability or microbial activity facilitated by pH buffering, alteration in CEC, and chelation.

Composts, manures and other nutrient-rich biological amendments can have a direct fertiliser effect associated with their high macronutrient content. Other inputs, including micronutrient preparations, also seek to address nutrient deficiencies or constraints preventing crops from accessing micronutrients. Composts, manures and biosolids all contain micronutrients in varying quantities that differ in availability to plants and soil microorganisms. The macro- and micronutrient contents of a range of commonly available biological amendments and feedstocks have been tabulated (Quilty and Cattle, 2011).

Biological amendments may alter chemical properties of soil including the form and content of organic matter, soil pH, the concentration of phytotoxic aluminium, and CEC. Some of these effects are mediated by microbial activity. Matured composts and biochars can have strong pH and nutrient buffering capacities, and may be acidic, neutral or alkaline. Soil pH is one of the primary drivers of microbial community structure and function (Rousk et al., 2010). A pH effect can be substantial in acidic soils where composts and manures (Wong et al., 1998; Wong and Swift, 2003) and biochars (Macdonald et al., 2014) have significant liming effects. Alleviation of acidity can influence plant yield in soils with a risk of aluminium toxicity (Wong et al., 1995). The application of organic resources such as compost, manure or biochar can also increase CEC, especially in clay-poor soils, enhancing production due to increased nutrient availability and reduced nutrient leaching (Quilty and Cattle, 2011).

3.3. Physical mechanisms

Soil structure is key to soil function and its ability to support ecosystem productivity (Young and Ritz, 2000). Biological amendments can influence the physical structure of soil by increasing the pore space for water/gas storage and movement, the rooting matrix for plants, and the habitable space and proximity to resources for biological communities. Consequently these amendments may improve crop growth and the resistance and resilience of production systems to stresses or perturbation.

Biological amendments can act both directly or indirectly on physical properties of soil. The most direct way by which biological amendments alter the physical structure of soil is through incorporation of organic matter. Organic matter influences the way soil absorbs and stores water, and responds to external (e.g. compaction and wind/water forces) and internal (shrinking and swelling during moisture fluctuations) pressures. In turn, organic matter supports biological activity, which acts to indirectly influence the processes of soil aggregation through microbial activity (Juma, 1993, Six and Paustian, 2014). By increasing soil porosity, soil organic matter can reduce bulk density (e.g. Zebarth et al., 1999); which is conducive to improved plant growth and microbial function (Beylich et al., 2010). Indirect impacts of biological amendments on the physical properties of soil can be facilitated through manipulation of communities of soil organisms that alter root growth and root architecture, stimulate secretion of polysaccharides into soil, or increase hyphal growth in soil. All of these have potential to influence the physical condition of soil indirectly by changing the habitat of soil fauna and microorganisms and consequently their function both quantitatively and/or qualitatively.

The type of organic matter and its residence time influence the role it plays in supporting physical transformations in soil (Bronick and Lal, 2005). Different types of organic matter influence various processes for different lengths of time. The well-established aggregate hierarchy proposed by Tisdall and Oades (1982) provides a model to guide understanding of how organic matter acts to alter the soil physical structure, where: i) complex aromatic organic structures provide more persistent agents associated with molecular level binding between organic matter and mineral surfaces; ii) biological exudates (polysaccharides, lipids, proteins and organic acids) provide transient bonding of particles at a microaggregate scale ($< 250\,\mu m$); and iii) roots and fungal hyphae provide temporary physical enmeshment at the macro-aggregate scale ($> 250\,\mu m$).

In addition to the bio-physical interactions which occur when biological amendments are added to soil as discussed above, interactions between chemical and physical soil properties also occur. Some biological amendments influence the cation balance in soils and the associated binding and precipitation reactions. Cations (e.g. Si^{4+}, Fe^{3+}, Al^{3+}, Ca^{2+}) increase precipitation of (hydr)oxides, phosphates, and carbonates which can enhance aggregation and formation of peds through chemical bonding (Tisdall and Oades, 1982). In soils with good structure, the pore space facilitates water and air movement and lowers bulk density. In heavy clay soils, poor structure can restrict water and air movement, while in coarse textured soils water retention can be problematic due rapid to drainage. At both ends of the scale, biological amendments can be used to improve structure, and indirectly influence chemical as well as biological processes that support plant growth.

In addition to aggregation, it is valuable to consider how some amendments might alter the surface area within soil, and the consequences this has for microbial colonisation. Young et al. (2008) demonstrated how soil physical processes influences microbial distribution within soil. They also discuss organic matter as a provider of a large surface area suitable for microbial colonisation, and that the three-dimensional structure and inter-connectivity within soil influences microbial function. Solid organic amendments, such as biochars, manures, and composts are more likely to influence the colonisation surfaces and the location of nutrient resources to a greater extent, and for longer duration, than are more labile amendments.

Considering the above physical mechanisms, amendments most likely to contribute to altered physical functions include: (i) animal manures and composts through complex C, transient binding, cation reactions and enmeshment; (ii) biochar amendments which are expected to have persistent effects associated with complex C, cation binding, enmeshment and their capacity to increase surface area; and (iii) amendments that are largely composed of simple labile C sources because they are expected to have transient binding impacts although they are relatively short lived (Fig. 1).

3.4. Plant-related mechanisms

Some biological amendments have the potential to modify plant physiology directly, promoting nutrient use efficiency and growth, and enhancing their tolerance to stresses such as temperature extremes, drought and salinity (Table 8). Although the modes of action of many biostimulants are not fully understood, a range of hypotheses have been proposed (Yakhin et al., 2017).

The auxin-like effect of some biostimulants such as humic substances and seaweed extracts has been shown to promote root growth and development of lateral roots (Crouch and van Staden, 1993; Jindo et al., 2012a). These effects can enhance nutrient acquisition through increased soil exploration and accelerated nutrient uptake (Rose et al., 2014). Other biostimulants such as chitosan act against bacterial, fungal and viral plant diseases by direct anti-microbial activity and by eliciting plant defence mechanisms, for example, through the production of phytoalexins that inhibit the soil borne pathogenic fungi such as *Fusarium* spp. (Badawy and Rabea, 2011; Hadwiger, 2013).

Table 8
Examples of potential benefits and modes of action of non-microbial biostimulants (Du Jardin, 2012; Traon et al., 2014).

Biostimulant type	Crop Benefit	Proposed Modes of Action
Chitosan	Reduced diseases	Direct effect on pathogens and indirectly by eliciting plant defence mechanisms. Physical and chemical barrier to diseases.
Amino acid-containing products	Increased tolerance to salinity, heat, drought and cold	Enhanced concentration of inert compatible osmolytes in tissues. Enhanced activity of plant growth regulators and of antioxidant enzymes.
Humic substances	Improved root growth and nutrient uptake. Increased tolerance to salinity, heat, drought and cold	Enhanced activity of plant growth regulators. Enhanced concentration of inert compatible osmolytes in tissues. Complexation and detoxification of aluminium and improved uptake of micro-nutrients
Seaweed extracts	Increased root growth and nutrient uptake. Increased tolerance of salinity, heat, drought and cold	Contains plant nutrients, oligosaccharides, amino acids and plant hormones that may act synergistically. Enhanced concentration of inert compatible osmolytes in tissues. Enhanced activity of plant growth regulators and antioxidant enzymes.

Adverse effects of drought, salinity and temperature extremes result in osmotic and oxidative stress in plants, which occurs as a result of excessive loss of water by evapotranspiration during drought or at high temperatures and loss of water by osmosis in saline conditions. At low temperatures, cells with low concentrations of osmolytes freeze more easily and are more prone to frost damage. Osmotic control is therefore important in tolerance to salinity and a range of climatic stresses. In this context, betaines are organic osmolytes contained in humic substances and seaweed extracts involved in plant protection against osmotic stress, drought, salinity or frost (Ertani et al., 2014; Zhang et al., 2003; MacKinnon et al., 2010). These substances rarely act independently in plant tolerance to abiotic stress because osmotic stress also gives rise to oxidative stress that can be ameliorated by anti-oxidants.

Accumulation of reactive oxygen species, superoxide anions and hydrogen peroxide can cause oxidative stress, damaging DNA, lipids, carbohydrates and proteins (Khan et al., 2009). Exogenous application of proline can relieve this by increasing the activity of antioxidant enzymes (Ertani et al., 2013). Amino acids such as asparagine, histidine, proline and serine improve the tolerance of stressed plants by stabilising proteins, enzymes and cellular structures and maintaining cell turgor by regulating ion transport and stomatal conductance (Anjum et al., 2014b; Botta, 2012). Cytokinins present in humic substances and seaweed extracts are also thought to be associated with drought tolerance (Khan et al., 2009).

4. Conclusions

Scientific evidence of field-scale benefits of most biological amendments with potential for use in rain-fed agriculture, is not widely available except in specific cases such as those associated with the legume inoculant industry. The research approach developed for legume inoculant selection, effectiveness evaluation, assessment of inoculant persistence and survival in soil, as well as accreditation, is a valuable model for use with other biological amendments, including generalist microbial inoculants.

Various forms of organic amendments applied to soil have potential to modify the conditions which facilitate microbially-mediated biogeochemical processes that improve soil health and increase nutrient use efficiency. However, the quantities of organic amendments required to make a significant contribution in rain-fed agriculture are often not available. Nevertheless, there is good evidence that long-term use of a number of these materials can be more beneficial than retention of stubble alone in cropping systems. Therefore, there is potential to capture some of these benefits if the research that underpins their use in farming systems is thorough and accessible.

Finally, many of the different kinds of biological amendments available for use in rain-fed agriculture have not been experimentally evaluated, although field studies can be used to make predictions. However, it is unlikely that peer-review research on all biological amendments will become available to farmers. Evidence of benefits of specific biostimulants in agriculture need to include field studies in addition to tissue and pot experiments. Therefore, a staged approach to research and development is required that combines (i) an understanding of compositional variation within and between amendment types and how this relates to likely performance in improving underlying soil constraints (see Fig. 1); (ii) small scale, controlled environment studies that aim to identify the specific mode(s) of action and under what circumstances they are most likely to operate; and (iii) targeted on-farm trials that evaluate performance under a range of environments and systems approaches.

Development of tools that allow the comparison of soil biological amendments based on their composition and likely impact of key soil biological, chemical, and physical functions is required to provide a framework to guide decision-making by farmers, consultants and policy makers. This assessment would be worthwhile where biological amendments have potential to be the main line of products available to improve crop tolerance to adverse seasonal conditions. These conditions are expected to occur more frequently as a result of climate change so research that discriminates among biological amendments with different levels of effectiveness is timely.

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