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# Use and understanding of organic amendments in Australian agriculture: a review

*J. R. Quilty*[A,B] *and S. R. Cattle*[B]

[A]Cotton Catchment Communities Cooperative Research Centre, Narrabri, NSW 2390, Australia.
[B]Faculty of Agriculture, Food and Natural Resources, The University of Sydney, NSW 2006, Australia.
[C]Corresponding author. Email: J.Quilty@usyd.edu.au

**Abstract.** A wide range of organic amendments (OA) is currently available to Australian farmers. These products have numerous agronomic applications, including the supply of plant nutrients, control of pests and diseases, and in management of soil health. Several of these products are also used in contaminated and degraded land remediation. The most commonly identifiable groups of OA in Australia are composts, compost teas, vermicasts, humic substances, meat, blood and bone meal, fish hydrolysates, seaweed extracts, bio-inoculants, biodynamic products, and biochars. Many of these OA contain nutrients within organic molecular structures; these nutrients are usually not immediately available to plants and must first be mineralised. Mineralisation often occurs as OA are consumed by microbes, thereby stimulating soil microbial activity. The application of OA such as bio-inoculants, humic substances, and seaweed extracts can potentially stimulate crop growth and development through the actions of plant growth-promoting hormones, including cytokinins, auxins, and gibberellins. Yet despite these apparent benefits, the widespread adoption of OA in Australia has been limited, due in part to the high application rates required to produce agronomic benefits, a lack of consistency in the composition of some products, a poor public perception of their utility, and a lack of unbiased scientific research into the agricultural potential of these products.

**Additional keywords:** bio-inoculant, compost, fish hydrolysate, humic substance, land application of organic waste, meat blood and bone meal, organic fertiliser, seaweed extract, vermicompost.

## Introduction

In Australia, a large range of commercially available products, known commonly as *organic fertilisers* or *organic amendments* (OA), is marketed to landowners, but there has been relatively little scientific scrutiny of their efficacy in broadacre agriculture. As these products are derived from naturally occurring organic materials, many have been certified for application in organic farming systems. However, many are not certified, either because they have not been put through the process of certification or, in the case of those derived from materials such as sewage sludge, because they may not meet the criteria of the certifying bodies, such as the National Association of Sustainable Agriculture Australia (NASAA 2008).

The sources of organic material used to manufacture OA include composted and uncomposted organic wastes from agricultural, industrial, and municipal operations, seaweeds, meat blood and bone meal, and humic substances (Eghball and Power 1999; Conn and Franco 2004; Imbufe *et al*. 2005; Curnoe *et al*. 2006; Nastri *et al*. 2006; Sivasankari *et al*. 2006; Hargreaves *et al*. 2008*b*; Mondini *et al*. 2008). Various microbial species have also been used to improve crop performance and soil health (Fließbach *et al*. 2009), while the casts of earthworms are a key component of some OA (Gutierrez-Miceli *et al*. 2007).

Several OA are used commonly only in horticultural industries and organic farming systems at present, but historically many were utilised in other agricultural systems. Before the widespread introduction of synthetic inputs during the first half of the 20th Century in developed countries (Cavert 1956) and the start of the 21st Century in the developing world (e.g. India and parts of Africa) (Jenkinson 2001; Ghosh 2004), various forms of OA were relied on to maintain soil fertility and crop yields, and to control agricultural pests and diseases. Manufacturers of OA usually suggest that the benefits of application will include one or more of the following: improvements in growth and yield of crops through the supply of plant nutrients, the control of pests and diseases, enhancement of the efficiency of synthetic inputs, and improvements to soil health (Table 1). Despite the claims of manufacturers and the existence of a modest body of research detailing the possible effects of OA application (e.g. Abbasi *et al*. 2003; El-Tarabily *et al*. 2003; Tenuta and Lazarovits 2004; Imbufe *et al*. 2005; Horii *et al*. 2007; Mondini *et al*. 2008), there has been little scientific investigation of the utility of these products in broadacre farming systems.

The current proliferation of OA in the marketplace is possibly due to the modern emphasis on maintaining and improving 'soil health', as well as the increased demand of consumers for


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**Table 1. A selection of organic amendments manufactured in Australia for agronomic utilisation, with the range of suggested application rates, estimated costs and purported benefits described by the supplier/manufacturer**

Information drawn from suppliers and manufacturers of organic amendments published and available on the internet

| Product type, recommended rate, estimated cost | Claimed benefits of application of the products |
|---|---|
| **Composts** | Microbial action makes the nutrients and minerals more available to plants |
| Pelletised products: | Adds nutrients and organic matter to the soil which release nutrients slowly |
| Application rates 0.075–5 t/ha | Promotes microbial and earthworm activity and facilitates greater nutrient retention |
| Cost $100–$500/t | Humus form which is the base for the production of humic and fulvic acids |
| Non-pelletised products: | Improves soil structure and enhances the soils cation exchange capacity |
| Application rates 0.5–30 t/ha | Supply of organic matter, nutrients, and beneficial microbial species |
| Cost $7–$800/t | Soil conditioner and economic nutrient supply |
| | Increases carbon in the soil plant growth and yield |
| | Enhance suppression of plant diseases |
| **Vermicasts** | Contains fulvic and humic acids which hold and penetrate liquids into plant crops |
| Liquids: | Biologically activated fertiliser used to correct nitrogen deficiencies |
| Application rates 10–100 L/ha | Increase penetration of nitrogen into the plant at extremely high and efficient rates |
| Cost $1–$20/L | A soluble plant food with nutrients up to 800% more available than other composts |
| Solids: | Biologically active with a host of beneficial aerobic bacteria and fungi |
| Application rates 2–50 t/ha | Humic acids release vital minerals within the soil to become available to plants |
| Cost $250–$1000/t | Concentrated and natural blend of micro and macro nutrients |
| | Promotes vegetative growth, flowering, and fruiting of all plant types |
| | Releases minerals, elements, and plant growth stimulants already existing in the soil |
| | Beneficial bacteria and fungi when applied to plant foliage can reduce pest infestation |
| | A natural, highly concentrated whole plant food |
| | Increased plant disease resistance |
| **Humic substances** | Liquid humic acids and organic catalysts |
| Liquids: | Increases soil water-holding capacity and reduces erosion potential |
| Application rates 1–30 L/ha | Stimulates enzymes and encourages soil microorganisms |
| Costs $4–$25/L | Increases cell permeability, root respiration, and nutrient translocation |
| Solids: | Increases cation exchange capacity of the soil and improves soil pH buffering capacity |
| Application rates 0.025–1 t/ha | Improves retention of water soluble fertilisers in the soil |
| Costs $40–$800/t | Cellulose and lignite create humic energy in the soil |
| | Stimulates beneficial microbial activity and root growth |
| | Improves nutrient uptake in hydroponic plants |
| | Increased retention and penetration of calcium in soil |
| **Meat, blood and bone meal** | Provides a source of nitrogen, phosphorus, and calcium |
| Liquid products: | Improves soil structure |
| Application rates 1–30 L/ha | Promotes beneficial soil microorganisms |
| Cost $10–$30/L | Encourages earthworms |
| Solid products: | Increased plant growth and yield |
| Application rates 0.1–1.2 t/ha | Balanced supply of nitrogen, phosphorus, and potassium |
| Cost $800–$1200/t | Organic matter including amino acids, albumin, globulin, cholesterol, and calcium |
| | Growth promotants, tricontanol and gibberellic acid |
| | Reduces waterlogging plant stress |
| | Reduces plant stress recovery time |
| **Fish hydrolysate** | Organic nitrogen, phosphorus, potassium combination based on fish protein formulation technology |
| Application rates 2–60 L/ha | Immediately available natural source of nutrients |
| Cost $15–$25/L | Promotes beneficial microorganisms and earthworm activity |
| | Promotes greater efficiency of other fertilisers |
| | Higher yields and improved food and nutrient levels for grazing |
| | Contains amino acids, albumin, globulin, cholesterol, humic acid and protein |
| | Manufactured using a low temperature, natural enzyme process |
| | Nitrogen in peptides and amino acids increase the availability of nitrogen |
| | Natural chelating properties |
| **Seaweed extracts** | Liquid extract of *Eklonia maxima* seaweed |
| Application rate 0.5–20 L/ha | Bull kelp (*Durvillaea potatorum*) is composted in a low temperature process |
| Cost $10–$30/L | Extract produced using 'cold cell burst method' |
| | Active ingredients are growth hormones in auxins and cytokinins |
| | Revitalises soil and assists in uptake of key nutrients |
| | Increases microbial activity, water retention, root growth and vigour |

(*continued next page*)

**Table 1.** (*continued*)

| Product type, recommended rate, estimated cost | Claimed benefits of application of the products |
|---|---|
| | Assists in plant stress recovery and reduces nutrient leaching |
| | Contains trace elements, vitamins, amino acids, plant growth hormones, enzymes |
| | Organic plant growth stimulant or soil revitaliser |
| **Bio-inoculants** | As a soil drench this creates biological barrier around roots and provides nutrients |
| Application rates 1–20 L/ha | Biochemical and biological disease control |
| Cost \$10–\$75/L | Builds soil aggregate structure, improving water-holding capacity |
| | Contains a range of soil microbial organisms which translocate soil nutrients to plants |
| | Liberate plant available nitrogen, and improves nutrient retention in the soil |
| | Provides a barrier of beneficial organisms when applied as a foliar spray |
| | Enhances carbon sequestration and nitrogen fixation |
| | Mineralisation of phosphorus, potassium, and trace elements and synthesis of Vitamin B12 through cobalt |
| | Generates $CO_2$ which opens up the soil reducing tillage requirements |
| | Crop residues are recycled and beneficial micro-flora are re-established |
| | A microbial soil activator containing bacteria, fungi, yeast and trace elements |

organically produced food (Lockie *et al*. 2004). Kibblewhite *et al*. (2008) describes the health of agricultural soil as its ability to support agronomic activity and maintain ecosystem services. Many government agencies across Australia have embraced this concept, instituting 'healthy soils programs' to encourage farmers to invest in maintaining and improving the health of their soils (McKenzie 1998; MacEwan 2007). In a survey of Australian cotton growers that investigated issues related to soil health, Shaw (2005) found that while OA had not been widely adopted by farmers (21% had used or were using OA on a trial basis, and 13% regularly applied OA), those who were utilising OA were often doing so as part of a soil health program. Typically, OA manufacturers claim that their products will improve the health of soil by increasing the organic carbon (OC) content, the availability of plant nutrients, microbial biomass and activity, and by enhancing soil structural stability (Table 1).

Although various studies suggest potential benefits to plant and soil from the utilisation of OA, a common finding is that the large application rates required to produce these benefits limit the adoption of these products (Albiach *et al*. 2001; Edmeades 2002). However, as the world moves towards low carbon economies and as the availability of resources such as phosphorus declines (Cordell *et al*. 2009), the importance of recycling nutrients for agronomic purposes from agricultural, industrial, and municipal wastes is likely to increase. In addition, the difference in cost between organic and synthetic, inorganic amendments is likely to diminish as global energy demands and costs increase (Dorian *et al*. 2006) and finite nutrient resources are depleted (Cordell *et al*. 2009). Under such circumstances, OA may become increasingly prominent soil and crop husbandry inputs, especially OA with multiple functionalities.

The objectives of this review are 3-fold. First, we categorise the large range of OA currently available in Australia, based on source material and composition. Second, we explore the purported benefits of applying the different groups of OA to plant–soil systems and review the scientific literature to determine the efficacy of these amendments. Third, we discuss why adoption of OA in Australia has been relatively slow, and why OA will become increasingly important in Australian agricultural systems. For the purposes of this review, non-synthetic organic fertilisers and/or organic amendments, both certified and otherwise, are referred to as OA. The naming of any specific products, manufacturers, suppliers, or certifying bodies does not represent an endorsement from the authors.

## Types of organic amendment currently, or potentially, used in Australian agriculture

In Australia, a large range of commercially available products can be identified as OA. Many have a history that can be traced back to the earliest efforts of humans to manage the soil for agricultural production (Semple 1928; Aimers and Rice 2006). Yet, since early last century, OA have been largely restricted to use in intensive horticultural industries and organic farming systems. This can be attributed to the advent of synthetic amendments for agricultural systems. The transition from organic to synthetic inputs in European agricultural systems occurred between 1870 and 1914 due to the decreasing cost and increasing availability of synthetic inputs, along with pressure on farmers to produce greater yields per hectare (van Zanden 1991). This period of agricultural change is identified as the first 'Green Revolution' (van Zanden 1991). From that time, there was a marked increase in the use of synthetic fertilisers (McGregor and Shepherd 2000) and a concomitant decrease in the use of OA. As a consequence of these changes, there is a community perception that the use of OA is in the domain of organic or alternative farming systems with little or no application to conventional agriculture.

We describe below the main types of OA available in Australia, including the source materials and typical constituents of the amendments and the claimed benefits of their application.

### *Composted organic matter*

Composting involves biologically mediated, oxidative processes that result in the formation of humified organic

material, improving the stability and suitability of highly heterogeneous organic matter for agricultural and horticultural application (Zmora-Nahum *et al*. 2007; Hargreaves *et al*. 2008*b*). Composted organic material has been used for agronomic purposes around the world for many centuries (Chan *et al*. 2007*a*). For example, animal dung was composted by farmers in the Mediterranean region as early as 800 BC, when the application of this OA to agricultural land was identified as beneficial to the performance of crops in subsequent seasons (Semple 1928). Composts produced for agronomic application are often made from crop residues, organic matter sourced from municipal and industrial waste materials, and manures from intensive animal production systems such as beef feedlots. Although composition can be variable, composted OA are generally good as a source of plant macro- and micro-nutrients and as a method of adding OC to the soil (He *et al*. 2001; Monaco *et al*. 2008) (Table 2). Such amendments may also improve structural condition and lead to an increase in microbial biomass within soil (Gopinath *et al*. 2008).

Where composts have been used in broadacre agriculture, application rates are generally 2–30 t/ha (Table 1), while in horticultural systems, application rates often exceed 30 t/ha (Table 3). Composts are usually spread over the surface of the soil, often followed by incorporation into the topsoil, both to improve soil condition and to supply plant nutrients (Eghball and Power 1999). Some farmers and horticulturists produce their own composts, but there are also many commercially manufactured compost products available in Australia. Potential problems and risks associated with the production and application of composts include the possibility of contamination by weed seeds, heavy metals, salts, and pathogens, as well as compositional inconsistencies (Chan *et al*. 2007*a*; Hargreaves *et al*. 2008*b*). Although use of composts produced from municipal solid wastes and biosolids is becoming more common, concerns remain about the potential of this source of compost feedstock to contain contaminants in the form of heavy metals and salts (Hargreaves *et al*. 2008*b*). Of all composts, those produced from animal manure have the greatest risk of harbouring viable weed seeds; the process of composting reduces, but does not eliminate, the risk (Larney and Blackshaw 2003). Government policy (DEWHA 2003), research efforts (Smidt *et al*. 2008), and the development and promotion of industry standards through groups such as the Waste Management Association of Australia aim to improve the quality, safety, and consistency of composts.

### *Compost tea/extract*

Compost teas or extracts are liquid OA used as a source of plant macro- and micro-nutrients, as a vector for beneficial microorganisms, and to control pests and diseases (Scheuerell and Mahaffee 2002; Hargreaves *et al*. 2009*a*, 2009*b*). They are usually produced at the site of application by farmers or gardeners, rather than being supplied by manufacturers. Compost teas are produced following recipes that can be obtained from horticultural and agricultural organisations such as the National Sustainable Agriculture Information Service in the USA, or Australian Soil Additives and Products Pty Ltd in Australia. The preparation of compost tea usually involves steeping compost in water for a defined period, often adding other substances such as seaweed extracts, fish hydrolysates, or molasses to the mixture. The resulting liquid is then applied as a foliar spray or a soil drench at rates ranging from 50 to >1000 L/ha, and often applied to cover the total leaf area of crops when used in pest and disease control, rather than at a specified rate. As indicated in Table 2, compost teas do not supply a substantial amount of plant macro- or micro-nutrients at low volumes. However, when applied at high rates, for example 1000 L/ha, they are potentially a useful nutrient source. Researchers have investigated the potential of compost teas produced with a range of composts including municipal solid wastes (Carballo *et al*. 2008), animal manures (Hargreaves *et al*. 2009*a*), and horticultural by-products (Diánez *et al*. 2006); although benefits have been identified, their efficacy has been highly variable.

### *Vermicasts*

Vermicomposting is a method of generating OA using earthworms (e.g. *Eisenia fetida*) to break down organic waste materials. As earthworms digest and excrete organic matter, worm castings, or vermicasts, are produced (Atiyeh *et al*. 2002; Arancon *et al*. 2006; Padmavathiamma *et al*. 2008). This natural process has been commercially adapted to produce OA from municipal and industrial wastes (Campitelli and Ceppi 2008), as well as from animal manures and plant biomass (Atiyeh *et al*. 2000; Singh and Sharma 2002; Arancon *et al*. 2006; Padmavathiamma *et al*. 2008). The resulting OA are solid vermicasts or vermicompost and vermicast liquid extracts. These products are a moderate source of plant macro- and micro-nutrients (Table 2) and humified organic matter, and contain microbial species that inhabit the digestive tracts of earthworms (Atiyeh *et al*. 2002; Sinha *et al*. 2010). The manufacturers of vermicast products suggest application rates of 10–100 L/ha for liquid amendments and 2–50 t/ha for solid amendments (Table 1).

### *Humic substances*

Humic substances occur naturally in soil and water, forming as organic matter decomposes (Hayes and Clapp 2001; Atiyeh *et al*. 2002; Smidt *et al*. 2008). The definition of humic substances is still debated due to their heterogeneous nature (Hayes and Clapp 2001); however, they can be classified into three main groups: humic acids, fulvic acids, and humin. These groups are distinguished by their solubilities in strong acid and base solutions. Fulvic acids are soluble at all pH values, humic acids are soluble only in strong acid, and humin is insoluble at all pH values (Sala *et al*. 2000; Hayes and Clapp 2001).

Commercially, humic substances are extracted from materials such as composted and vermicomposted organic matter, coal, and peat. For example, humic substances are extracted from leonardite, a brown coal, to produce an OA (Brownell *et al*. 1987; Imbufe *et al*. 2005). Humic substance based OA are available in both liquid suspension and solid form; liquid suspensions are usually mixed with water and applied to the soil or plant foliage, while the solid granular products are either spread and incorporated into the soil or combined with

**Table 2. Feedstock and macro- and micro-nutrient content of a range of commonly available organic amendments**

| Feed stock | Macronutrient (g/kg) | | | | | | | Micronutrients (mg/kg) | | | | | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | N | P | K | S | Ca | Mg | Fe | Zn | Mn | Cu | Na | |
| *Composts* | | | | | | | | | | | | | |
| Municipal solid waste | 195 | 19 | 6.5 | 6.7 | 9.9 | 65 | 4.5 | 5930 | 184 | 840 | 80 | 5520 | Hargreaves *et al.* (2009*a*, 2009*b*) |
| Ruminant manure | 238 | 20 | 5.8 | 3.9 | 6.6 | 16 | 4.3 | 7280 | 302 | 684 | 25 | 326 | |
| Olive husk, cattle manure, poultry manure | 424 | 13 | 4.1 | 9.2 | | 14 | 4 | | | | | | Riahi *et al.* (2009) |
| Olive husk, poultry manure | 344 | 18 | 7.4 | 7.2 | | 15 | 3.5 | | | | | | |
| Olive mill waste | 479 | 25 | 2.4 | 26.7 | | | | | | | | | Walker and Bernal (2008) |
| Municipal solid waste | | | 6.4 | 6 | 9.1 | 53 | 4 | 6110 | 175 | 740 | 81 | 4900 | Hargreaves *et al.* (2008*a*, 2008*b*) |
| Ruminant manure | | | 12 | 6.5 | 6.2 | 12 | 4.1 | 7300 | 224 | 526 | 23 | 527 | |
| Tea waste | 391 | 42 | | 3.2 | | 1.7 | 20 | 40 320 | 11 | 27 | 23 | | Morikawa and Saigusa (2008) |
| Coffee waste | 340 | 34 | | 15 | | 7.1 | 32 | 41 430 | 25 | 789 | 16 | | |
| Banana waste, cow dung | 308 | 7 | 1.8 | 10 | | | | | | | | | Padmavathiamma *et al.* (2008) |
| Kelp extract | | 24 | 4.2 | | | 37 | 12 | 1100 | 200 | 700 | | | Alvarado *et al.* (2008) |
| Shredded municipal waste | 144 | 11 | 0.2 | | | | | | | | | | Tognetti *et al.* (2007) |
| Shredded municipal waste, wood shavings | 222 | 9 | 0.1 | | | | | | | | | | |
| Swine manure | 49 | 2 | 6.8 | 2.2 | 2.1 | 16 | 5.5 | 1899 | 106 | 119 | 74 | | Chang Chien *et al.* (2007) |
| Green waste | 206 | 12 | 3.8 | 4.4 | 1.9 | 22 | 2.9 | 14 300 | 190 | | 85 | 1600 | Chan *et al.* (2007*a*) |
| Green and kitchen waste, paper, cardboard | 255 | 17 | 0.2 | 5.3 | 0.2 | 0.4 | 0.1 | 157 | 2.9 | 2.8 | 1.2 | 632 | Dimambro *et al.* (2007) |
| Green waste, fruit and vegetable waste | 118 | 10 | | 2.7 | 0.4 | 0.2 | 0.1 | 108 | 0.7 | 1.5 | 0.3 | 432 | |
| Municipal, kitchen, commercial waste | 373 | 19 | 0.1 | 3.1 | 0.7 | 10 | 0.9 | 70 | 39 | 41 | 13 | 2512 | |
| *Vermicomposts* | | | | | | | | | | | | | |
| Biogas slurry | 186 | 28 | | 2.7 | | 4.9 | | 989 | 26 | | 33 | | Raja Sekar and Karmegam (2010) |
| Banana waste, cow dung, *Eudrillus eugineae* | 143 | 13 | 2.4 | 14 | | | | | | | | | Padmavathiamma *et al.* (2008) |
| Banana waste, cow dung, *Eisenia fetida* | 150 | 10 | 2.1 | 11 | | | | | | | | | |
| Banana waste, cow dung | 180 | 10 | 2.2 | 10 | | | | | | | | | |
| Household waste, cow dung, *Perionyx sansibaricus* | 339 | 32 | 7.9 | 16 | | | | | | | | | Suthar (2007) |
| Vegetable waste, leaf litter, *Perionyx sansibaricus* | 201 | 20 | 6.4 | 9.7 | | | | | | | | | |
| Grape marc, composted straw and manure | 209 | 17 | | | | | | | | | | | Flavel and Murphy (2006) |
| Cattle manure | 522 | 13 | 3.4 | 3 | | | | | | | | | Loh *et al.* (2005) |
| Goat manure | 530 | 12 | 6.5 | 3.4 | | | | | | | | | |
| Food waste | 195 | 13 | 27 | 92 | 26 | | 44 | | | | 50 | 842 | Arancon *et al.* (2004) |
| Paper waste | 172 | 10 | 27 | 92 | 18 | | 45 | | | | 47 | 986 | |
| (1) Wheat straw, *Pleurotus sajor-caju* | 153 | 7.6 | 1.6 | 5.2 | | | | | | | | | Singh and Sharma (2002) |
| (2): (1) + *Trichoderma harzianum* | 149 | 8.7 | 1.7 | 5.2 | | | | | | | | | |
| (3): (2) + *Azotobacter chroococcum* | 149 | 8.9 | 1.7 | 5.2 | | | | | | | | | |
| (4): (3) + *Aspergillus niger* | 126 | 9.8 | 1.9 | 5.5 | | | | | | | | | |
| Wheat straw | 165 | 7 | 1.5 | 5.1 | | | | | | | | | |
| Pig manure, *Eisenia fetida* | | 47 | 2.2 | 15 | | 0.8 | 0.1 | 0.7 | | | | | Atiyeh *et al.* (2002) |
| Food waste, *Eisenia fetida* | | 47 | 1 | 26 | | 2.2 | 0.3 | 4.4 | | | | | |
| *Biodynamic composts* | | | | | | | | | | | | | |
| Grape pomace, dairy manure, straw | | | 3.7 | 19 | | 12 | 5.2 | | | | | 1.8 | Reeve *et al.* (2010) |
| Farmyard manure | 394 | 22 | 46 | 216 | | | | | | | | | Zaller and Köpke (2004) |

(*continued next page*)

**Table 2.** (*continued*)

| Feed stock | Macronutrient (g/kg) | | | | | | | Micronutrients (mg/kg) | | | | | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | N | P | K | S | Ca | Mg | Fe | Zn | Mn | Cu | Na | |
| Dairy manure and bedding | 332 | 12 | 0.3 | 7.6 | | | | | | | | | Carpenter-Boggs *et al.* (2000) |
| *Compost teas/extracts* | | | | | | | | | | | | | |
| Chicken manure compost | | | | 0.42 | | 0.04 | 0.02 | 1.9 | 0.6 | 0.2 | 0.7 | 65 | Koné *et al.* (2010) |
| Bovine manure compost | | | | 0.01 | | 0.01 | <0.01 | | | 0.04 | 0.1 | 8 | |
| Seaweed compost | | | | 0.16 | | 0.02 | 0.01 | 1.3 | 0.3 | 0.4 | 0.3 | 46 | |
| Shrimp compost | | | | 0.01 | | 0.01 | <0.01 | 0.1 | | | 0.1 | 9 | |
| Municipal solid waste compost (2006) | | | <0.01 | 0.24 | 0.17 | 0.06 | 0.02 | 0.8 | 0.1 | 0.2 | 0.1 | 301 | Hargreaves *et al.* (2009*a*, 2009*b*) |
| Municipal solid waste compost (2005) | | | <0.01 | 0.11 | 0.07 | 0.02 | <0.01 | 3.8 | 0.3 | 0.3 | 0.2 | 124 | |
| Ruminant manure compost (2006) | | | 0.03 | 0.23 | 0.05 | 0.04 | 0.04 | 0.8 | 0.1 | 0.1 | 0.1 | 29 | |
| Ruminant manure compost (2005) | | | 0.01 | 0.09 | 0.01 | 0.01 | 0.01 | 0.5 | 0.01 | 0.01 | 0.01 | 13 | |
| Mature rice straw compost | | 24 | 25 | 20 | | 45 | 9.3 | 1545 | 244 | | | | Siddiqui *et al.* (2009) |
| Palm oil empty fruit bunches compost | | 16 | 18 | 11 | | 54 | 2.3 | 589 | 217 | 113 | | | |
| Municipal solid waste compost | | | 0.01 | 0.17 | 0.10 | 0.04 | 0.01 | 3.3 | 0.2 | 0.4 | 0.2 | 182 | Hargreaves *et al.* (2008*a*, 2008*b*) |
| Ruminant manure compost | | | 0.03 | 0.18 | 0.04 | 0.03 | 0.03 | 2.2 | 0.1 | 0.2 | 0.0 | 23 | |
| Spent mushroom compost | | | <0.01 | 0.31 | | 0.10 | 0.03 | 0.3 | 0.1 | 0.2 | 0.1 | 64 | Michitsch *et al.* (2007) |
| Municipal solid waste compost | | | 0.01 | 0.31 | | 0.02 | 0.01 | 0.5 | 0.1 | 0.1 | 0.04 | 173 | |
| Chicken manure compost (anaerobic) | | | | 0.41 | 0.07 | 0.06 | 0.12 | | | | | | Welke (2005) |
| Cattle manure compost (aerobic) | | | | 0.20 | 0.02 | 0.01 | 0.01 | | | | | | |
| *Humic substances* | | | | | | | | | | | | | |
| Unspecified | 163 | 6.4 | 0.2 | 22 | | 12 | 3.1 | 615 | 611 | 24 | 36 | | Alagöz and Yilmaz (2009) |
| Leonardite | 594 | 13 | | | | | | | | | | | Elena *et al.* (2009) |
| Leonardite | 622 | 12 | | | | | | | | | | | |
| Unspecified | | 42 | 0.4 | 38 | 0.18 | 0.04 | 0.01 | | | | | | Eyheraguibel *et al.* (2008) |
| Soil humic substance | 508 | 44 | | | | | | | | | | | Antelo *et al.* (2007) |
| Unspecified | | 1.5 | 6 | 48 | 0.9 | 0.4 | | 5000 | | | | 700 | Imbufe *et al.* (2005) |
| Lignitic coal | 540 | 50 | 6 | | | | | | | | | | Sharif *et al.* (2002) |
| Vermicompost | 377 | 45 | | | 18 | | | 44 | | | | | Alves *et al.* (2001) |
| Vermicompost | 427 | 67 | | | 13 | | | 11 | | | | | |
| Sewage sludge | 563 | 65 | | | | | | | | | | | Ayuso *et al.* (1997) |
| Municipal waste and sewage sludge compost | 539 | 71 | | | | | | | | | | | |
| Peat | 583 | 19 | | | | | | | | | | | |
| Leonardite | 609 | 9.4 | | | | | | | | | | | |
| Commercial product | 632 | 20 | | | | | | | | | | | |
| Coal | 424 | 9.6 | | | | | | 18 | | | | | Garcia *et al.* (1993) |
| Unspecified | 633 | 6.8 | 1.5 | | 45 | | | | | | | | Malcolm and MacCarthy (1986) |
| *Biochars* | | | | | | | | | | | | | |
| *Eucalyptus grandis* | 498 | 6.1 | | | | | | | | | | | Dias *et al.* (2010) |
| Papermill waste | 500 | 4.8 | | 0.1 | | 2.5 | 0.3 | | | | | 218 | van Zwieten *et al.* (2010) |
| Papermill waste | 520 | 3.1 | | 0.4 | | 4.4 | 0.6 | | | | | 851 | |
| Corn cobs | 776 | 8.5 | | | 0.2 | | | | | | | | Mullen *et al.* (2010) |
| Corn stover | 573 | 14.7 | | | 1.5 | | | | | | | | |
| Laurel residues | 563 | 31 | | | | | | | | | | | Ertaş and Hakki Alma (2010) |
| Yeast derived | 674 | 50 | | | | | | | | | | | Steinbeiss *et al.* (2009) |
| Glucose derived | 646 | <0.01 | | | | | | | | | | | |
| Timber industry residue | 870 | 3.1 | 0.05 | 1.2 | | 1.8 | 0.1 | | | | | | Asai *et al.* (2009) |

(*continued next page*)

**Table 2.** (*continued*)

| Feed stock | Macronutrient (g/kg) | | | | | | | Micronutrients (mg/kg) | | | | | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | N | P | K | S | Ca | Mg | Fe | Zn | Mn | Cu | Na | |
| Soybean oil cake | 646 | 85 | | | 1.4 | | | | | | | | Tay *et al*. (2009) |
| Soybean oil cake | 810 | 0.6 | | | 0.5 | | | | | | | | |
| Rape | 447 | 8 | | | 6 | | | | | | | | Sánchez *et al*. (2009) |
| Sunflower | 436 | 10 | | | 3 | | | | | | | | |
| Chicken litter | 380 | 20 | 0.01 | | | | | | | | | | Chan *et al*. (2008) |
| Chicken litter | 330 | 8.5 | 1.8 | | | | | | | | | | |
| Green waste | 360 | 1.8 | 400 | 8.2 | | 0.2 | 0.1 | | | | | 552 | Chan *et al*. (2007*b*) |
| *Eucalyptus deglupta* | 824 | 5.7 | 0.6 | | 0.3 | | 1.3 | | | | | | Rondon *et al*. (2007) |
| Broiler litter | 258 | 7.5 | 48 | 30 | 6.4 | | | | | | | | Lima and Marshall (2005) |
| Broiler cake | 172 | 6 | 73 | 58 | 8 | | | | | | | | |
| Sewage sludge | 470 | 64 | 56 | 1.7 | 5 | | | | 1700 | | 2600 | 2 | Bridle and Pritchard (2004) |
| *Meat, blood, and bone meals* | | | | | | | | | | | | | |
| Meat and bone meal | 460 | 111 | 27 | 2.9 | | 69 | 1.4 | 337 | | | | | Cayuela *et al*. (2009) |
| Blood meal | 526 | 164 | 2 | 6.9 | | 1.1 | 0.2 | 2144 | | | | | |
| Meat and bone meal | | | | 6.3 | 4.6 | | 2.4 | 127 | 183 | 2.7 | | 7939 | Dybowska *et al*. (2009) |
| Meat and bone meal heated to 725°C | | | | 14 | 17 | | 9.6 | 2741 | 499 | 109 | | 25 080 | |
| Meat and bone meal heated to 850°C | | | | 14 | 19 | | 10 | 4461 | 492 | 171 | | 20 021 | |
| Cattle blood ash | | | | | | | | | 670 | | 80 | | Radomskaya *et al*. (2008) |
| Non-defatted | 354 | 80 | 57 | | 3.8 | | | | | | | | Mondini *et al*. (2008) |
| Defatted | 307 | 86 | 68 | | 3.9 | | | | | | | | |
| Meat and bone meal bottom ash | | | 162 | | | 288 | 12 | 15 000 | 262 | | | 27 000 | Coutand *et al*. (2008) |
| Meat and bone meal fly ash | | | 78 | 81 | | 127 | 5 | 5000 | 1349 | | | 86 000 | |
| Meat and bone meal fly ash washed | | | 154 | 25 | | 246 | 13 | 14 000 | 3373 | | | 44 000 | |
| Meat and bone meal laboratory ash | | | 189 | 15 | | 282 | 7 | 1000 | 373 | | | 24 000 | |
| Bovine/swine | 431 | 94 | | | | | | | | | | | Cayuela *et al*. (2008*b*) |
| Bovine | 339 | 78 | 57 | | | | | | | | | | |
| Defatted bovine | 299 | 84 | 68 | | | | | | | | | | |
| Swine | 414 | 90 | 28 | | | | | | | | | | |
| Meat and bone meal | 557 | 15 | | | 6 | | | | | | | | Skodras *et al*. (2007) |
| Demineralised meat and bone meal | 529 | 73 | | | 7.9 | | | | | | | | |
| *Fish hydrolysate* | | | | | | | | | | | | | |
| Unspecified | | 22 | 27 | 3 | | 6 | 0.3 | 229 | 75 | 12 | | | Wiens and Reynolds (2008) |
| Unspecified | | 60 | 20 | | | | | | | | | | Lester *et al*. (2007) |
| Yates Ltd fish emulsion | 25 | 4.5 | 1.8 | 1.2 | 1.3 | 1.1 | 0.03 | 3000 | 300 | 200 | 50 | 155 000 | El-Tarabily *et al*. (2003) |
| Cod | | 9.8 | 5 | 0.8 | | 6.4 | 0.2 | 65 | 51 | 10 | 6.0 | | Blatt (1991) |
| Cod and perch | | 10 | 4.4 | 1 | | 5.6 | 0.1 | 59 | 52 | 7.0 | 3.0 | | |
| Unspecified | | 24 | 0.9 | 2.5 | | 3.1 | | | | | | | Wyatt and McGourty (1990) |
| Unspecified | | 2.3 | 4.5 | 0.5 | | | | | | | | | DeMoranville (1989) |
| *Seaweed extract* | | | | | | | | | | | | | |
| *Kappaphycus alvarezii* | | 5.8 | 0.1 | 19 | 11 | 0.5 | 0.7 | 130 | 22 | 7.5 | 9 | 5.8 | Zodape *et al*. (2009) |
| *Kappaphycus alvarezii* | | 0.03 | <0.01 | 2 | 0.1 | 0.05 | 0.1 | 11 | 0.6 | 2.5 | | 0.01 | Rathore *et al*. (2009) |
| Unspecified | | 2 | 8 | 3 | | | 9 | 55 | 11 174 | 6.3 | | | Wiens and Reynolds (2008) |
| *Ascophyllum nodosum* | | 12 | | | 15 | 4.5 | 3.5 | 165 | 38 | 13 | 3 | 40 000 | Hurtado *et al*. (2009) |
| *Gracilaria tenuistipitata* | | 0.5 | 1.1 | 11 | | 10 | 5.8 | 129 | 37 | 1571 | 15 | 11 600 | Hong *et al*. (2007) |
| *Kappaphycus alvarezii* | | 4.7 | 0.9 | 23 | | 6.8 | 13 | 190 | 21 | 5.4 | 9.9 | 26 800 | |
| *Sargassum mcclurei* | | 13 | 0.8 | 13 | | 98 | 18 | 1301 | 34 | 159 | 11 | 19 800 | |
| *Sargassum wightii* | | | 0.05 | 0.2 | 0.1 | 0.2 | 0.1 | 0.9 | 1 | | 1.5 | 506 | Sivasankari *et al*. (2006) |
| *Caulerpa chemnitzia* | | | | 0.1 | 0.02 | 0.2 | 0.1 | 0.3 | 1.2 | | 1 | 176 | |
| Unspecified | | 10 | 1.1 | 24 | | 12.3 | 15 | | | | | | Astatkie *et al*. (2006) |
| *Dictyota dichotoma* | | 196 | | 120 | | 192 | | | 1220 | 2130 | 980 | 176 000 | Sasikumar and Panneerselvam (2005) |
| *Ascophyllum nodosum* | | 0.7 | 0.1 | 1.9 | | 1.3 | 0.8 | 135 | 33 | 128 | 1.5 | | Blatt (1991) |

**Table 3. Organic amendment application rate and verified scientific outcome of utilisation**
MSW, Municipal solid waste

| Feedstock | Application rate | Scientifically verified result of application | References |
|---|---|---|---|
| | | *Compost* | |
| MSW | 25–100 t/ha | High variability of the product resulted in high variability of growth response in radish | Chan *et al*. (2007*a*) |
| Beef cattle feedlot manure | 145 t/ha | Significantly lower maize grain yields than synthetic fertiliser | Eghball and Power (1999) |
| MSW, anaerobically digested sewage sludge and ovine manure | 24 t/ha | Enhanced biological activity | Albiach *et al*. (2000) |
| Cow manure, grape marc, wheat straw, orange peel | 500 g/kg | Reduced disease incidence and pathogen population size in cherry tomatoes | Raviv *et al*. (2005) |
| Sewage sludge | 80 t/ha | Increased microbial activity and carbon mineralisation | Fernandez *et al*. (2007) |
| MSW and treated sewage sludge | 30–60 t/ha | Increased carbon mineralisation and increased soil organic matter | Pedra *et al*. (2007) |
| Paper mill waste | 22–78 t/ha | Increased soil carbon content and enhanced water use efficiency of potato production | Foley and Cooperband (2002) |
| | | *Vermicompost* | |
| MSW, horse and rabbit manure, and chicken manure | 10–20 t/ha | Improved soil structural stability, organic carbon content, and increased microbial respiration | Ferreras *et al*. (2006) |
| Vermicompost | 2.4 t/ha | Insignificant effect on soil biology | Albiach *et al*. (2000) |
| Vegetable and leaf litter with microbial inoculant | 100–500 mL/L | Reduced incidence of collar rot in chickpea | Sahni *et al*. (2008) |
| | | *Biodynamic compost* | |
| Biodynamic farm yard manure compost | 30 t/ha | Increased earthworm biomass | Zaller and Köpke (2004) |
| | | *Compost tea/extract* | |
| Ruminant and MSW | 58 L/ha | K concentration within strawberry leaves increased while Na concentration decreased | Hargreaves *et al*. (2009*a*) |
| | | *Humic substance* | |
| Brown coal derived humic substances | 0.05–10 g/kg | Improved acidic-soil structural condition | Imbufe *et al*. (2005) |
| Coal and peat derived humic acids | 20 g/kg | Improved soil structural condition | Yamaguchi *et al*. (2004) |
| Ca-saturated coal derived humic substances | 10 t/ha | Effectively reduced exchangeable Al content of acidic soil | Peiris *et al*. (2002) |
| Humic substance | 100 L/ha | Insignificant effect on soil biology | Albiach *et al*. (2000) |
| | | *Biochar* | |
| Poultry litter biochar | 10–50 t/ha | Improved vegetable yield and enhanced synthetic fertilizer efficiency | Chan *et al*. (2008) |
| | | *Meat, blood, and bone meal* | |
| Meat and bone meal | 20 g/kg | Reduced mobility of Zn, Pb, Cd in contaminated soil | Sneddon *et al*. (2006) |
| Meat and bone meal | 20 g/kg | Reduced the viability of fungal pathogen *V. dahliae* microsclerotia | Tenuta and Lazarovits (2004) |
| Meat and bone meal | 35 g/kg | Increased growth of tobacco and immobilisation of Pb in contaminated soil | Deydier *et al*. (2007) |
| Meat and bone meal | 2.5–5 t/ha | Increased N availability and increased soil microbial content and activity | Mondini *et al*. (2008) |
| | | *Fish hydrolysate* | |
| Yates Ltd fish emulsion | 33 mL/kg | Enhanced production of plant growth-promoting substances by soil microbes | El-Tarabily *et al*. (2003) |
| | | *Seaweed extract* | |
| Seaweed extract | 33–195 L/ha | Improved yield and nutrient uptake of soybean | Rathore *et al*. (2009) |
| | | *Bioinoculant* | |
| *Pseudomonas tolaasii, P. fluorescens, Alcaligenes* sp., *Mycobacterium* sp. | $40^8$ CFU/seed | Increase biomass of canola in Cd contaminated soils | Dell'Amico *et al*. (2008) |

synthetic inputs before application. Application rates suggested by manufacturers typically range from 1 to 30 L/ha for liquid products applied as foliar sprays or soil drenches, while granular humic substances are spread at rates of 25–>400 kg/ha (Table 1).

### *Meat, blood, and bone meal*

*Circa* 700 BC, it was noted by Greek and Roman farmers that on battle fields where many bodies were left behind, crop yields would be enhanced in the following seasons (Semple 1928). More recently, meat, blood, and bone meal (MBBM), a by-product of meat processing industries, has been used commonly as both an OA and a supplement feed source for production animals. With the outbreak of mad cow disease in Europe in the late 1990s, and its subsequent appearance elsewhere around the world, the practice of feeding MBBM to production animals has been banned in many countries (Coutand *et al*. 2008; Mondini *et al*. 2008). Consequently, there is a renewed focus on MBBM products as a soil–plant OA. MBBM products are usually sold in solid form, either as pellets or granules, which are spread over the soil and incorporated. Although less common, liquid MBBM products are also available to be applied as a soil drench, through fertigation, or as foliar sprays. MBBM products are applied as a rich source of plant nutrients (Table 2) (Blatt 1991; Mondini *et al*. 2008), to manage soil-borne pests and diseases (Tenuta and Lazarovits 2004), and as an input used in the remediation of contaminated soil (Hodson *et al*. 2001).

The nutrients in MBBM are predominantly found within fats and proteins, and become available to plants as these compounds mineralise in the soil (Cayuela *et al*. 2008*b*). Manufacturers claim that MBBM is an effective source of nitrogen (N), a claim supported by the findings of Jeng *et al*. (2006), Mondini *et al*. (2008), and Cayuela *et al*. (2009). The producers of solid MBBM products suggest application rates of 0.1–>1 t/ha, while the rates suggested for liquid forms are ~30 L/ha (Table 1). The rates found by researchers to achieve positive crop responses have generally been $\geq$0.5 t/ha (Jeng *et al*. 2006).

### *Fish hydrolysates*

By-products from fishery industries were often applied to improve the fertility of soil in areas close to the coast in Europe and the United States until the early 19th Century (Fussell and Goodman 1941; Sherman 1979). Today, fish hydrolysates are produced by hydrolytic or enzymatic breakdown of by-products from the processing industries of fish such as tuna or mackerel (Andarwulan and Shetty 1999). The removal and subsequent processing of feral fish species from waterways is another production pathway in Australia. Application methods for fish hydrolysates suggested by the manufacturers include fertigation, foliar spraying, and soil drenching. Recommended application rates for fish hydrolysate products are typically 10–30 L/ha for foliar spray and 20–60 L/ha when applied as a soil drench (Table 1). The most commonly cited benefit of fish hydrolysates is the addition of plant nutrients (Table 2) (Blatt 1991), but they have also been used to enhance disease resistance in plants (Abbasi *et al*. 2003), and to improve germination and seedling performance (Andarwulan and Shetty 1999; Kristinsson and Rasco 2000; Horii *et al*. 2007).

### *Seaweed extracts*

In the United Kingdom from the end of the 18th Century and through the 19th Century, seaweed was applied either directly to agricultural land after being collected from the shore, or after being burnt or composted, and was often mixed with other organic materials (Fussell 1948; Sherman 1979). Early in the 20th Century in the United States, seaweed was harvested and burnt to produce a source of potassium for agricultural use (Cameron 1913). The use of untreated or burnt seaweed as an amendment is no longer common, but seaweed extracts are now frequently found in the OA market. Seaweed extracts are produced using seaweed species such as *Ecklonia maxima* and *Durvillaea potatorum* (Tay *et al*. 1985; Stirk and van Staden 1996), usually via extraction methods designed to increase the level of enzymes and hormones contained in the final liquid product. Consequently, seaweed extracts contain the plant growth hormones cytokinins, suggested to be responsible for enhanced crop performance (Stirk and van Staden 1996; Stirk *et al*. 2004; Sivasankari *et al*. 2006). Application rates for seaweed extracts generally range from 0.5 to 5 L/ha for foliar application and from 5 to 20 L/ha when used as a soil drench (Table 1).

### *Other uncomposted organic waste materials*

While composting is often used to stabilise organic wastes and reduce the heterogeneity of raw materials, there are many uncomposted, municipal, industrial, and agronomic waste products that are used, or have been applied, as OA. Olive and paper mill waste (Curnoe *et al*. 2006; Brunetti *et al*. 2007), treated sewage sludge and biosolids (Pedra *et al*. 2007), and uncomposted animal manures (Liu *et al*. 2009) have all been used as ameliorants to improve soil condition and crop performance. Industrial, agronomic, and municipal solid wastes materials are increasingly being used as feedstock for energy creation through the process of pyrolysis. However, some of these waste products are also being used in the production of biofuels, biodiesel and bioethanol, the by-products of which have also been utilised as OA (Johnson *et al*. 2004; Moore *et al*. 2010). These include waste materials from the distillation of wheat, corn, sugar beet, and other crop residues, and biomass from algae used in the production of biodiesel (Chisti 2008; Moore *et al*. 2010). Such amendments may provide a supply of plant nutrients and OC to the soil, possibly enhancing both soil health and crop performance (Chisti 2008; Moore *et al*. 2010).

The application of raw organic waste materials can carry risks including the introduction of weeds, pathogens, and toxic compounds into the environment (Cameron *et al*. 1997; Larney and Blackshaw 2003). While the value of recycling nutrients from materials such as biosolids and industrial by-products is recognised by regulatory bodies in Australia, there are often human and environmental health risks associated with the application of untreated wastes (NRMMC 2004). Federal and State Government agencies, such as the Victorian Environmental Protection Authority, regulate the land

application of industrial and municipal solid wastes in Australia to prevent the accumulation of contaminants and to reduce the risk of spreading human and animal pathogens, as well as agronomic pests and diseases. In New South Wales, waste applied to land as a fertiliser or soil amendment must be shown to be beneficial and not cause harm to the environment. 'Resource Recovery Exemptions' for land application permit the application of a range of wastes, each facilitated by prescribed conditions that vary depending on the risk of environmental harm posed by that waste (DECCW 2008). Resource Recovery Exemptions have been developed for, among others, treated grease trap waste, food waste compost, and organic outputs from the processing of mixed municipal waste. Industrial wastes such as fly ash from coal combustion, and lime and gypsum residues from drinking water treatment and plasterboard, may also be applied to land in New South Wales for the purposes of growing vegetation (DEC 2005). Although OA such as paper mill residues and sewage sludge are not commercially manufactured, they continue to be utilised due to their ability to enhance land management efforts; therefore, we have given them some consideration in this review.

### Bio-inoculants

Bio-inoculants, or microbial inoculants, are OA that contain living microbial species considered beneficial to agronomic or horticultural production systems. These products, often consisting of microbial species in a liquid suspension, contain organisms such as arbuscular mycorrhizal fungi (Gianinazzi *et al*. 1995), *Azospirillum* (Okon and Itzigsohn 1995), and *Pseudomonas* sp. (Walsh *et al*. 2001), are used to improve crop production through improved nutrient uptake by plants, sequestration of atmospheric nitrogen, or via control, inhibition, or competition with plant pathogens and pests (Table 1). While much scientific literature is available on the viability of inoculating agricultural soils with microbial species, the focus has been predominantly on microorganisms that form symbiotic relationships with plant roots, such as rhizobia that fix atmospheric nitrogen in leguminous agro-ecosystems (Deaker *et al*. 2004) and arbuscular mycorrhiza (Parniske 2008). Research in Australia on the efficacy of biological inoculants that introduce free-living microorganisms (species that do not require direct interaction with plant roots) to soil with the aim of enhancing microbial diversity, nutrient cycling, and soil health, is limited.

A range of bio-inoculants, commonly referred to as *stubble digesters*, is applied to increase the decomposition rate of crop residues. The development of such products is in response to the need for improvements in crop residue management techniques as farmers move from conventional farming systems to reduced and no-till practices (Davis *et al*. 2008). The large number of stubble digesters available in Australia suggests that farmers are exploring alternative methods to manage stubble loads and to control pathogens that reside on the remnants of previous crops. Almost no scientific literature is available on the application and efficacy of these products.

Bio-inoculants are usually applied through soil injection or sprayed over stubble. Soil injection rates are generally 20–30 L/ha (Table 1), while the suggested application rates for stubble digesters are 15–25 L/ha.

### Biodynamic amendments

Biodynamic farming, a form of organic agriculture developed by Rudolf Steiner (Steiner 2005), relies on OA to manage pests and diseases, to supply plant nutrients, and to maintain soil health. Composts and compost teas are inputs regularly used in biodynamic farming enterprises. These are produced using a variety of animal manures and plant materials, one of which, BD500, is produced using cow manure packed into a cow horn and buried for 6 months over autumn–winter. The contents of the cow horn are then mixed with water and applied in the same manner as a compost tea (ATTRA 1999). There is some evidence that these products may suppress several plant fungal pathogens (Rupela *et al*. 2003) and may increase the level of fungi in the soil (Ryan and Ash 1999). Zaller and Köpke (2004) studied the effects of biodynamic composts and traditionally composted farmyard manure on soil chemical and biological properties over a 9-year period. A significant increase in earthworm abundance was found in the soil treated with biodynamic compost, compared with a soil treated with traditionally composted farmyard manure. There is, however, a lack of scientific literature on the application of biodynamic inputs in conventional systems; instead, most of the research has focused on comparing the two farming methods. The holistic theory that underpins biodynamic farming is possibly the reason for this, as the production of biodynamic amendments such as BD500 is specifically for application in a biodynamic agricultural system. As a result, biodynamic products such as BD500 are not widely available to farmers using conventional methods of agriculture. However, as Watson *et al*. (2008) describes, the transfer of knowledge between organic, biodynamic, and conventional farming has been slow but is likely to increase in the future. Therefore, biodynamic products are considered in this review.

### Biochar

Biochar, or agrichar, is generally a solid, fine, granular, black charcoal material produced by slow pyrolysis of biomass often sourced from agricultural or forestry industries. The manufacturers of biochar claim that it can improve soil fertility, enhance the efficiency of synthetic inputs, and increase the OC content of the soil. Unlike many other OA, much research has been undertaken on biochar in recent years, possibly because of the potential of biochar to sequester carbon in soil in a stable form and due to the energy produced during the production process (Lehmann *et al*. 2006; McHenry 2009). Research has shown that biochar can enhance the efficiency of synthetic nitrogen fertilisers (Chan *et al*. 2007*b*; Steiner *et al*. 2007; van Zwieten *et al*. 2010) and the biological nitrogen fixation potential of *Rhizobium*–legume systems (Rondon *et al*. 2007), as well as improving soil structural condition (Chan *et al*. 2007*b*) and increasing the carbon content of soil (Lehmann *et al*. 2006).

The energy produced during the oxygen-limited pyrolysis of biomass used to create biochar can be utilised to create electricity. When this source of energy is combined with the

potential carbon sequestration properties of biochar, the greenhouse gas emission footprint of the entire process is significantly lower than current fossil fuel energy production systems (Gaunt and Lehmann 2008). However, despite the potential benefits, biochar is currently not widely available in Australia, partly due to the difficulty manufacturers face in obtaining sufficient amounts of biomass for the pyrolysis process and variability in biomass availability over time. Biochar application rates used in research have ranged from 10 to >140 t/ha.

## Purported and demonstrated benefits of organic amendment use

Increasingly large numbers of OA are being aggressively marketed to farmers, with rural newspapers and other regional publications in Australia often containing articles, advertisements, and testimonials for these products. Such marketing gives anecdotal evidence of yield increases after the application of OA, improved soil health, and enhanced drought tolerance of crops, but little scientific research has been undertaken to qualify or quantify these claims.

### *Utilisation of organic amendments as a source of plant nutrients*

Perhaps the most common claim of OA manufacturers and suppliers is that their products represent a significant source of plant nutrients. Many OA can effectively provide plants with a source of nutrients, as the success of agriculture before the development of synthetic fertilisers attests. However, questions remain about the application rates of OA required to derive a plant nutritional benefit, with Edmeades (2002) concluding that where these products were found to have a positive influence on plant nutrition, the rates of application were many times greater than those recommended by the manufacturers.

Many OA are specifically produced to provide plants with macro- and micro-nutrients (Table 2). Some of these nutrients are in an inorganic form in OA such as composts and compost teas (Iglesias-Jimenez and Alvarez 1993; Hargreaves *et al*. 2009*a*). However, unlike synthetic fertilisers, significant proportions of the nutrients are contained within organic molecular structures (e.g. amino acids) and are therefore not immediately available to plants (Jeng *et al*. 2006). These nutrients become available as the organic molecules are mineralised in the soil, often by microorganisms (Dilly 2001; Cayuela *et al*. 2008*b*; Mondini *et al*. 2008). Manufacturers claim that plants are supplied with nutrients more efficiently through the mineralisation of the organic molecular structures within their products than via the application of synthetic fertilisers.

Several studies have demonstrated that OA can effectively supply nutrients to crops, maintaining yields at the same level as inorganic fertilisers (Blatt 1991; Jeng *et al*. 2006; Mondini *et al*. 2008). Using MBBM as a source of nitrogen, Jeng *et al*. (2006) identified a linear increase in yields of wheat (*Triticum aestivum*) with increasing application rates (500, 1000, and 2000 kg/ha), and yields of barley (*Hordeum vulgare*) maintained at the same level as with an inorganic fertiliser, when applied at a rate equivalent to 100 kg N/ha. In a comparison of MBBM, seaweed extract, fish hydrolysate, and a synthetic fertiliser in a vegetable production system, Blatt (1991) found the OA as effective as synthetic fertilisers in maintaining yields in 6 of 7 growing seasons when the organic products were applied at rates equivalent to 75 and 150 kg N/ha.

Mondini *et al*. (2008) investigated the influence of a MBBM on soil microbiological activity, biomass, and composition, along with the availability of nitrogen in the form of extractable ammonium ($NH_4^+$) and nitrate ($NO_3^-$). They found that MBBM enhanced nitrogen availability and microbial activity in soil, and led to an increase in the population size of both aerobic and anaerobic bacteria and fungi. Mondini *et al*. (2008) and Cayuela *et al*. (2008*b*) demonstrated the importance of temperature in the mineralisation process of organic molecules. The influence of temperature may explain why Smith and Hadley (1989) found that 20% of the nitrogen applied to a soil in the form of an OA did not appear to be accessible to microorganisms and remained unmineralised. In this case, the mineralisation rate may have been reduced due to the maximum treatment temperature of 20°C, which may have decreased microbial activity. However, Smith and Hadley (1989) found that the addition of both a dried-blood derived OA and treated sewage sludge provided lettuce with a source of nitrogen that matched the plants' requirements more effectively than synthetic ammonium nitrate.

Jeng *et al*. (2006) found that plant-available phosphorus content increased in soil amended with MBBM and concluded that this OA supplied adequate phosphorus to barley and rye grass (*Lolium perenne*) for more than one season with a single application of 500 kg/ha. Padmavathiamma *et al*. (2008) increased the amount of plant-available nitrogen and phosphorus in a vermicompost through the addition of nitrogen-fixing microbial species – *Azotobacter, Azospirillum*, and *Rhizobium* – to the vermicomposting process. The levels of $NH_4^+$ and $NO_3^-$ were greater in the treated vermicompost, as was the amount of phosphorus, which was >1.5%, as opposed to 0.5% in the conventionally processed product. In other research, Ghosh *et al*. (2008) found an enhanced concentration of available nitrogen and phosphorus in soil amended with 50 L/ha of a vermicast product. They concluded that this was due to an increased mineralisation of nitrogen and phosphorus occurring in the soil as a result of the OA stimulating activity in the microbial biomass.

Other industrial and municipal treated waste products can also provide a source of nutrients for crop production. Waste materials including paper mill waste (Curnoe *et al*. 2006), olive mill waste (Nastri *et al*. 2006; Sierra *et al*. 2007), treated sewage sludge or biosolids (Moritsuka *et al*. 2006; Chan *et al*. 2007*a*), municipal solid wastes (Wolkowski 2003; Tognetti *et al*. 2007), by-products from bio-fuel production (Moore *et al*. 2010), and fly ash (Jala and Goyal 2006) have all been used for their nutrient value as OA in research. The use of municipal and industrial waste materials in the production of OA may provide a recycling opportunity that adds value to waste products and offers farmers an alternative to synthetic inputs.

Liquid OA appear to have poor ability to provide a consistent agronomic benefit at an economically viable application rate; Edmeades (2002) concluded that the application rates of liquid organic fertilisers used to produce a positive yield response are often uneconomical. Evidence suggests that the application

rates required to gain agronomic benefits from solid OA may also be economically prohibitive. Assuming MBBM contains ~8% nitrogen, as suggested by Jeng *et al*. (2006), the rates of MBBM applied by Blatt (1991) would be 937 and 1875 kg/ha, while Jeng *et al*. (2006) used MBBM at 1250 kg/ha. These rates are unlikely to be considered economically viable in Australian broadacre agricultural systems, especially when transport costs are included. However, the application of OA at lower rates in combination with synthetic fertilisers may provide crops with sufficient nutrients, allowing a reduction in the amount of inorganic inputs required with the possible provision of some soil health benefits.

Although biochars do not provide a significant source of plant nutrients (Table 2) they can improve the efficiency of synthetic fertilisers (van Zwieten *et al*. 2010) and nitrogen-fixing capabilities of *Rhizobium* spp. in legume pasture and cropping systems (Rondon *et al*. 2007). van Zwieten *et al*. (2010) noted increased crop biomass from the addition of a paper mill waste biochar combined with a synthetic fertiliser, an effect that was not seen when the synthetic fertiliser was applied on its own. They also found that this effect was more variable in an alkaline soil than a mildly acidic soil and suggested that this may be due to the liming ability of the paper mill waste biochar. The findings of van Zwieten *et al*. (2010) suggest that while biochars may not provide a significant source of plant nutrients, they can improve the nutrient assimilation capability of crops where they are applied, by positively influencing the soil environment.

Since most OA contain plant nutrients in organic molecular structures which must first be mineralised (Jeng *et al*. 2006; Mondini *et al*. 2008), several questions relating to this process need to be answered to ensure the efficient use of these products as a plant nutrient source. Is a slow mineralisation process efficient, potentially reducing the loss of nutrients through leaching and volatilisation, providing plants with their requirements more effectively over a longer time period? What temperature must soils reach before the process of mineralisation enables the products to be of nutritional benefit to crops? What soil moisture content is required before mineralisation via the microbial biomass will effectively occur? The environmental and chemical processes influencing the mineralisation of OA in the soil need to be considered where the products are being applied for plant nutritional purposes.

### *Organic amendments applied to stimulate plant growth*

Some OA available in Australia are claimed by manufacturers to be capable of stimulating plant growth via growth-promoting hormonal activity of molecular structures within the amendments (Table 1). Research has identified humic substances (Brownell *et al*. 1987; Canellas *et al*. 2002; Arancon *et al*. 2006), seaweed extract (Stirk and van Staden 1996), and biological inoculants (Roesti *et al*. 2006) as OA capable of eliciting hormonal growth responses in crops such as cotton (*Gossypium* sp.), tomato (*Lycopersicon* sp.), maize (*Zea mays*), and wheat. Studies have also shown that stimulation of microbial species resulting from the application of fish hydrolysates (El-Tarabily *et al*. 2003) can lead to the production of plant-growth promoting substances in soil.

A small body of research demonstrates that claims made by OA manufacturers of enhanced root growth resulting from the application of their products may be correct (Canellas *et al*. 2002; Arancon *et al*. 2006; Eyheraguibel *et al*. 2008). Piccolo *et al*. (1992) and Nardi *et al*. (2002) both concluded that low molecular weight humic substances, particularly humic acids, are active stimulators of hormonal activity in plants. Nardi *et al*. (2002) suggest that low molecular weight humic substances are responsible for positive root-growth responses in peas (*Pisum sativum*) and increased nutrient uptake in barley. The small size of these humic substances allows them to reach the plant plasma membrane, where they effectively influence the assimilation of nutrients. Piccolo *et al*. (1992) also found that treatment with humic substances increased the uptake of nitrates by barley. Eyheraguibel *et al*. (2008) concluded that increased root elongation in germinating maize seed was the result of an interaction between plant hormones and a humic substance treatment.

Interestingly, much of the recent research into the interaction between plant hormonal activity and humic substances relates to those extracted from vermicomposts. These humic substances have been found to stimulate root growth in banana (*Musa* sp.), cassava (*Manihot* sp.), and cowpea (*Vigna unguiculata*) (Padmavathiamma *et al*. 2008), and increase $^{+}$-ATPase activity in maize roots (Canellas *et al*. 2002). Plant growth responses to vermicompost-sourced humic substances have also been seen in tomatoes, cucumbers (*Cucumis* sp.) (Atiyeh *et al*. 2002), marigolds (*Tagates patula* var. Antigua Gold F1), capsicums (*Capsicum annuum grossum* var. King Arthur), and strawberries (*Fragaria ananasa* var. Tribute) (Arancon *et al*. 2006). Growth and yield increases have also resulted from direct application of vermicomposts (Arancon *et al*. 2004; Ali *et al*. 2007); presumably, this is at least partly due to the activity of the humic substances contained in the OA. Arancon *et al*. (2006) also found that humic substances extracted from vermicompost produced a greater growth response in a range of horticultural crops than a commercial humic substance product, although they did not specify the source of the commercial product. This suggests that some intrinsic property or characteristic of vermicast-sourced humic substances is responsible for stimulation of plant growth.

Several studies have concluded that enhanced growth and development of a selection of horticultural and agricultural crops is due to the influence of plant growth-promoting hormones present in seaweed extract (Beckett and van Staden 1989; Crouch *et al*. 1990). Manufacturers of seaweed extracts suggest that the presence of cytokinins in their products will lead to improved crop performance (Table 1). Beckett and van Staden (1989) used a commercially available seaweed extract, Kelpak®, in a study of potassium-stressed wheat (*Triticum aestivum* L. cv. SST 66), and found that the seaweed extract application resulted in a yield increase and enhanced root growth in stressed plants, but had no effect on unstressed plants. Rathore *et al*. (2009) observed a 10% and 57% yield increase in soybean when seaweed extract was applied, derived from *Kappaphycus alvarezii*, as a foliar spray at rates of 16 and 98 L/ha, respectively, 30 and 60 days after sowing. Rathore *et al*. (2009) also observed increased nutrient uptake, but did not mention any changes in root architecture or physiology.

Crouch and van Staden (1992) concluded that auxins and cytokinins, active in seaweed extracts, were responsible for enhanced root growth in tomato plants, which in turn resulted in improved ability of the plants to assimilate nutrients from the soil. Zhang and Ervin (2004) also suggested that increased root growth in creeping bentgrass (*Agrostis palustris* Huds. A.) resulted from the activity of hormonal components of tested seaweed extracts and humic substances, and that the enlarged root biomass, in part, led to improved drought tolerance of this species, but the authors could not clearly identify the mechanisms responsible for this physiological change.

El-Tarabily *et al*. (2003) suggested that while fish hydrolysate is an effective source of plant nutrients, it is also responsible for stimulating growth-promoting hormones, in the form of auxins, cytokinins, and gibberellins, from the microbial populations in the treated soil. El-Tarabily *et al*. (2003) applied Yates Ltd Fish Emulsion® to radishes (*Raphanus sativus*) at a rate of 2 mL/L water every 10 days and concluded that fish hydrolysate is a suitable substitute for synthetic fertilisers in radish production on a sandy loam soil, and also suggested that the enhanced presence of growth regulators was partly responsible for the positive response of the crop to the OA. The findings of El-Tarabily *et al*. (2003) indicate that benefits may be gained through the application of fish hydrolysates and potentially a range of other OA, by applying the products through irrigation systems (fertigation).

Inoculation of soil with non-rhizobial, beneficial microbial species is a technique that is increasingly used in agricultural research throughout the world, but has not been widely commercialised (Vessey 2003). A study in Italy found that the biomass of canola (*Brassica napus*) was increased in soil inoculated with bacterial species that produce indole acetic acid (IAA), a naturally occurring plant hormone that can promote root growth (Dell'Amico *et al*. 2008). Soil inoculation was also used by Gravel *et al*. (2007), who observed increased growth and yield in tomatoes resulting from the addition of two microbial species, *Pseudomonas putida* and *Trichoderma atroviride*. Egamberdiyeva and Höflich (2003) observed an increase in nutrient uptake, and root and plant growth of wheat grown in soil inoculated with a range of plant-growth promoting microbial species. These studies suggest that the microorganisms investigated elicit a positive growth response in plants via the production of substances at the soil–root interface. While Egamberdiyeva and Höflich (2003) found that the beneficial bacteria were capable of surviving in a range of non-indigenous soils, and despite the known benefits of plant-growth promoting bacteria, their efficacy when applied in the field is still highly variable and further research and development is required before this technology can be widely adopted in agriculture (Turnbull *et al*. 2001; Compant *et al*. 2010).

Seed treatment, or seed priming, is used by farmers to improve germination rates, seedling emergence, and seedling survival rates. Seed priming generally involves soaking crop seeds in a solution for several hours before sowing. In a study of seed priming, Horii *et al*. (2007) found that the use of a fish hydrolysate at 2.5 mL/L water increased the tolerance of maize to germination stress. Similarly, Andarwulan and Shetty (1999) showed that fish hydrolysates had potential benefits for the seed priming of peas (*Pisum sativum*) at a concentration of 2 mL/L. Other OA have also proved effective when utilised in seed priming. Improved germination rates were seen in radish after seeds were treated with seaweed extract (Friedlander and Ben-Amotz 1990), and enhanced root elongation in germinating maize was noted by Eyheraguibel *et al*. (2008) who used humic substances as a seed treatment.

While research indicates that the application rates needed for many OA as a source of nutrients may be uneconomical, the rates used to elicit a positive growth response in crops are often relatively low. Atiyeh *et al*. (2002) produced a positive yield response in tomato and cucumber using humic substances extracted from a cattle manure, food, and paper waste vermicompost applied at a rate of 50 mg C/L water; from available data, this carbon application rate equates to <250 mg humic substance/L (Table 2). Beckett and van Staden (1989) recorded a positive crop growth response when seaweed extract was applied at 0.25 mL/100 mL water. Zhang and Ervin (2004) reported enhanced root growth from the use of OA when seaweed extract was applied at 0.5 kg/ha and a humic substance at 1.5 kg/ha, and Arancon *et al*. (2006) used a humic substance applied at a rate of 250 mg/kg soil. These results suggest that these products may be useful in broadacre agriculture where they can aid in crop establishment, performance, and nutrient management. Refining the methods of applying OA by using techniques such as soil injection to ensure placement near the seed during sowing, or applying the OA as a pre-sowing seed treatment, may improve the utility of these products.

### *Utility of organic amendments in control of pests and diseases*

Organic amendments can reduce the impact of, or control, pests and diseases through increased diversity and activity of beneficial microbial species, improved resistance via enhanced growth and development of plants, and via the introduction or production of compounds that inhibit, deter, or kill pathogenic species (Akhtar and Alam 1993; Gamliel *et al*. 2000; Lazarovits *et al*. 2001; Postma *et al*. 2003; Tenuta and Lazarovits 2004). Research suggests that OA can potentially be used to manage a range of horticultural and agronomic pests and diseases. However, in Australia this application is largely limited to organic and biodynamic agriculture.

As a component of an integrated management system targeting soil-borne pathogens, MBBM, manures, and composts have been used to improve the efficiency of solarisation (Gamliel *et al*. 2000; Spadaro and Gullino 2005). Solarisation is a technique that involves covering soil infected by plant pathogens with a transparent film, usually plastic, during the warmer months of the year, to raise the temperature and increase the level of toxic gases (Spadaro and Gullino 2005). Several researchers have concluded that OA with high nitrogen content are capable of enhancing the build-up of ammonia ($NH_3$) and other toxic compounds in the soil during solarisation (Gamliel *et al*. 2000; Lazarovits *et al*. 2001; Tenuta and Lazarovits 2002; Raviv *et al*. 2005; Spadaro and Gullino 2005; Oka *et al*. 2007).

While solarisation is an effective method for controlling soil-borne pests and diseases, its application in broadacre

agriculture is restricted due to the difficulty of applying plastic covers over large areas. However, in some cases, OA can reduce the impact and population size of several soil-borne plant pathogens through the build-up of toxic compounds without the use of solarisation. For example, the application of MBBM successfully controlled plant parasitic nematodes (*Meloidogyine* sp.) and fungal and bacterial potato pathogens (Lazarovits *et al*. 2001). Tenuta and Lazarovits (2004) found that the application of MBBM significantly reduced the viability of verticillium wilt (*Verticillium dahliae*), a fungal plant pathogen with a wide range of potential hosts, due to the build-up of $NH_3$ and nitrous acid ($HNO_2$) in the soil to levels lethal to the microsclerotia of *V. dahliae*. Lazarovits *et al*. (2001) also effectively controlled *V. dahliae* with the application of a liquid swine manure at 5500 L/ha. Lazarovits *et al*. (2001) did not report the nitrogen content of the liquid swine manure used in their research; however, assuming ~5.5 g N/L (Chantigny *et al*. 2007), the amount applied would have equated to ~30 kg N/ha, and although the application rate of the manure may be prohibitive, the amount of nitrogen applied is relatively low. Thus, OA that contain relatively high levels of nitrogen, such as MBBM, fish hydrolysates, and some composts and vermicomposts (Table 2), may be suitable additions for integrated pest management strategies.

The ability of OA to increase the level of toxic compounds in the soil is influenced by the texture, OC content, and pH of a soil (Lazarovits *et al*. 2001; Tenuta and Lazarovits 2004; Conn *et al*. 2005). Where applied OA can influence soil pH and OC contents, the ensuing structural, biological, and nutritional improvements in the soil environment can lead to improved plant health and a corresponding increase in tolerance and resistance of plants to pests and diseases (Featonby-Smith and van Staden 1983; Janvier *et al*. 2007). For example, Sahni *et al*. (2008) used a vermicompost and an antagonistic microbial species, *Pseudomonas syringae*, to reduce the effects of collar rot in chickpea (*Cicer arietinum*), caused by the pathogen *Sclerotium rolfsii*. They concluded that improvements in soil and plant condition resulting from the application of the OA enhanced the ability of the antagonistic species to inhibit *S. rolfsii*.

Abbasi *et al*. (2003) applied fish hydrolysate as a foliar spray to combat bacterial spot on tomato and capsicum (*Capsicum annum*), resulting in reduced rates of infection and increased crop yields. The fish hydrolysate was applied weekly in a 0.5% concentration aqueous solution at a rate of ~25 mL/plant. Abbasi *et al*. (2003) hypothesised that the reduction in bacterial spot on treated plants may have been due to a nutritional effect, similar to that previously identified by McGuire *et al*. (1991), who used synthetic fertilisers to influence the concentration of nutrients in tomato plants and found that the population size of epiphytic pathogens was inversely correlated with potassium levels in the leaves. Abbasi *et al*. (2003) also used a neem oil product, produced from seed of the neem tree (*Azadirachta indica*), which enhanced the level of disease resistance through antimicrobial activity.

Olive mill waste residues have also been found to contain active phytotoxic, allelopathic, and antimicrobial compounds, which have been used to manage a range of plant pests and diseases (Kotsou *et al*. 2004; Bonanomi *et al*. 2006; Cayuela *et al*. 2008*a*). Cayuela *et al*. (2008*a*) applied composted and uncomposted olive mill waste extracts to reduce the pathogenicity of several fungal plant pathogens, the rate of egg hatching of root-knot nematode, and the motility of its juvenile second stage. Bonanomi *et al*. (2006) used olive mill dry residue waste to effectively control plant fungal pathogens. While olive mill wastes can control several plant pests and pathogens, this form of OA must be carefully applied, as the toxic compounds responsible for the phytotoxic and antimicrobial activity of these materials can potentially contaminate water bodies (Saadi *et al*. 2007).

Several OA have also been utilised to inhibit the growth of weed species. Boydston *et al*. (2008) concluded that dried distillers' grain had a herbicidal effect, reducing the emergence and growth of common chickweed (*Stellaria media*) when it was applied at a rate of 50 g incorporated/kg soil, and annual bluegrass (*Poa annua*) when applied at 100 g/kg soil. However, application of dried distillers' grain also had a significant negative impact on the ornamental species Red Sunblaze (*Rosa* hybrid), Franz Schubert (*Phlox paniculata*), and Nana (*Coreopsis auriculata*). Although surface-applied, dried distillers' grain was effective in reducing the emergence and growth of the weed species, this was only at rates >8000 t/ha. Cayuela *et al*. (2008*a*) used composted and uncomposted olive mill waste extracts to reduce the germination rate of the weed species *Amaranthus retroflexus* and *Solanum nigrum*. They concluded that the herbicidal effect of the olive mill waste OA was largely due to the presence of phenolic compounds. The longevity in the soil of compounds responsible for the herbicidal activity of these OA must be well understood, as they may also adversely affect the germination and growth of crop species.

The application of some composts may potentially introduce antagonistic microbial species to the soil, reducing the pathogenic potential of detrimental microorganisms through increased competition, predation, and via the production of inhibitory substances. Rupela *et al*. (2003) found that the biodynamic composts, BD500 and BD502, contained a variety of bacterial species that displayed antagonistic properties towards the fungal plant pathogen *Fusarium solani*. Compost teas have also been used to reduce the impact of plant pathogens by increasing the abundance and diversity of beneficial microbial species, stimulating systemic resistance in plants and via the deposition of inhibitory substances on crops at sites where infection may occur (Zhang *et al*. 1998; Al-Dahmani *et al*. 2003; Litterick *et al*. 2004; Diánez *et al*. 2006). In an incubation experiment, Diánez *et al*. (2006) used a compost tea produced from grape marc waste to inhibit the growth of several soil-borne phytopathogenic fungi; it was concluded that the production of siderophores by the microbial species within the compost tea was responsible for reducing the effects of the fungal pathogen. Siderophores are compounds excreted by some microbial species that bind with iron, thereby restricting its availability to competing microorganisms, potentially causing a reduction in their growth and development and, in some cases, their pathogenic abilities (Neilands 1981).

Al-Dahmani *et al*. (2003) significantly reduced the infection rate of bacterial spot of tomato with foliar application of a

compost tea produced with composted cow manure. Although bio-control agents such as *Trichoderma hamatum* were thought to be present in the compost tea, these were determined as not critical to the efficacy of the OA. The compost tea may have had a nutritional effect on tomato, similar to that of the fish hydrolysate treatment used by Abbasi *et al*. (2003), also combating bacterial spot. Al-Dahmani *et al*. (2003) found that compost teas produced using a range of materials and methods varied in their ability to control bacterial spot on tomato, indicating that the ability of these amendments to combat the effects of pathogens is related to the composts from which they are created and the methods used in their production.

There is considerable variation in the results of research into the efficacy of OA in managing agronomic pests and diseases (Bonanomi *et al*. 2010). One reason for this variability is compositional inconsistency of the products utilised. For example, composts and compost teas used for this purpose have been produced from a wide range of organic materials, such as pine bark, cow manure, and rice straw (Al-Dahmani *et al*. 2003; Siddiqui *et al*. 2009). Another source of variation is likely to be the environment in which the products are utilised. Siddiqui *et al*. (2009) suggested that the environmental conditions of the leaf surface of okra (*Abelmoschus esculentus* L.) reduced the survival of bio-control microbial species in a compost tea. However, many of these products have shown potential pest and disease management benefits, and as OA such as compost and compost tea are relatively easily produced on-farm, they are likely to become more widely adopted as further research determines their modes of action and how best to produce them for this purpose. When compared with the cost of chemical alternatives and the possible negative effects on soil biota that synthetic control agents such as copper-based fungicides can have (Bünemann *et al*. 2006), the use of OA as part of an integrated management strategy to control plant pathogens may be a suitable and affordable option for farmers.

### *Effects of organic amendments on soil organic carbon status*

There is ongoing debate over suitable indicators of soil health in agricultural and horticultural systems (Kibblewhite *et al*. 2008). However, there is a general consensus that OC plays an essential role in the soil environment and is an indicator of soil health (Bronick and Lal 2005; Lal 2006). Reversing the loss of soil carbon that has resulted from >100 years of agronomic activity in Australia can help improve soil health; however, the topical reason for improving the OC content of agricultural soils is carbon sequestration (Skjemstad *et al*. 2001; Mikha *et al*. 2006; Lal 2007; Park *et al*. 2007; Favoino and Hogg 2008). Soil OC is the second largest carbon pool on the surface of the earth after the oceans (Batjes 1996; Swift 2001), and the possibility of increasing the OC content of the soil through changing agronomic management practices may play a role in combating climate change (Lal 2002).

Maintaining OC is important not only for sequestration and greenhouse gas mitigation, it also has a significant influence on the physical, chemical, and biological properties of soil (Ashagrie *et al*. 2007). The application of OA, including anaerobically digested sewage sludge (Pedra *et al*. 2007), vermicomposts (Ferreras *et al*. 2006), composted animal and plant manure (Hati *et al*. 2006; Leite *et al*. 2007), MBBM (Cayuela *et al*. 2008*b*), oily food waste (Rashid and Voroney 2004), glucose (Park *et al*. 2007), and biochar (Lehmann *et al*. 2006; Ogawa *et al*. 2006), can lead to increased soil OC content. Enhancing the OC content of soil, especially in degraded agricultural land, will improve soil health (Bhogal *et al*. 2009), and may in the future offer farmers alternative revenue streams if carbon sequestered in soil is recognised in carbon markets or carbon pollution reduction schemes.

The carbon content of OA varies significantly, from >50% in some biochar to <1% in seaweed extract (Table 2). While products such as seaweed extract and bio-inoculants are not a direct source of carbon, the stimulation of plant growth by these OA (Zhang and Ervin 2004; Dell'Amico *et al*. 2008) will increase the amount of organic matter, and therefore OC, in the soil. An important question needs to be resolved in relation to any increase in soil OC: what is the longevity of this carbon in the soil? Stability and longevity of soil OC is related to the pool of carbon in which it resides, its molecular configuration, the soil chemistry, and its location within the soil matrix (Baldock and Skjemstad 2000; Ahn *et al*. 2009; Liu *et al*. 2009). The longevity of soil OC forms supplied in various OA is the subject of ongoing research (McHenry 2009; Tatzber *et al*. 2009).

A common finding of research into changes in soil OC related to the application of OA is that these products tend to increase microbial biomass carbon (Albiach *et al*. 2000; Karaca *et al*. 2006; Mondini *et al*. 2008). However, this increase may not be sustained without continued reapplication. For example, Karaca *et al*. (2006) showed that while microbial biomass and activity increased significantly 7 days after the application of humic substances, they declined to the initial levels 180 days post-application. There is also evidence that in some circumstances, application of OA may result in a long-term decline in soil OC content due to increased carbon mineralisation (Ghosh *et al*. 2008). Where OA stimulate soil biological activity, there is likely to be an increased rate of carbon mineralisation in the soil, potentially reducing the amount of OC. As Pedra *et al*. (2007) demonstrated, carbon mineralisation could be increased in soil by stimulating microbial activity through the addition of OA with relatively high amounts of organic nitrogen. They showed that addition of anaerobically digested sewage sludge with a low carbon to nitrogen (C/N) ratio elevated the rate of soil carbon mineralisation. The mineralisation rate was increased with the addition of the treated sewage sludge at 60 t/ha, but Pedra *et al*. (2007) also found that soil organic matter content increased with the addition of the sludge product at 30 t/ha and municipal solid waste compost at 30 and 60 t/ha.

Carbon mineralisation can have a negative impact on soil OC content. However, Marinari *et al*. (2007) found that enhanced microbial activity resulting from the application of vermicompost and manure led to an increased rate of humification, thus potentially increasing the amount of humified organic material in the soil. Humified organic matter contains carbon in a relatively stable form due to the resilience of humic molecular structures to biochemical decay and as a result of physical protection of these entities, as soil minerals bind

with the humified material (Piccolo *et al*. 1997; Hayes and Clapp 2001).

### *Soil structural benefits through the application of organic amendments*

While nutrient supply and plant growth stimulation are potential benefits from the application of humic substances, the most widely acknowledged function of this group of OA is improvement of soil structural condition. Addition of humic substances has been shown to improve aggregation in soils with a range of texture grades and mineral suites (e.g. Fortun *et al*. 1989, 1990; Piccolo *et al*. 1997; Imbufe *et al*. 2005; Margherita *et al*. 2006). Changes in structure resulting from the addition of humic substances were identified by Fortun *et al*. (1990) in a micromorphological study of a sandy loam and a calcareous clay soil. They noted that treatment of soil with a peat-extracted humic substance increased the number of small aggregates (<1000 µm), while application of a manure-extracted humic substance led to the formation of larger aggregates (1500–2500 µm). They concluded that this was probably due to differences in the molecular structures within the humic substances as a consequence of the two separate sources of OA. The improvement in aggregation resulting from the application of humic substances observed by Fortun *et al*. (1990) was greater in the clay soil than the sandy loam due to the greater number of binding sites available on clay minerals in the clay soil.

Varadachari *et al*. (1991) demonstrated the ability of humic substances to form bonds with clay particles, particularly 2 : 1 clay minerals such as smectite. They concluded that the majority of bonds formed between humic substances and clay minerals were via exchangeable cations forming a bridging link between the mineral surface and the humic molecular structures. Yamaguchi *et al*. (2004) studied the effect of humic substance application on soils of the Western Australian wheatbelt and found that the interaction of a humic substance with clay in the soil depended on both the source of the humic substance and the clay mineral suite. The use of coal-derived humic substances was more effective in producing stable clay aggregates than humic substances extracted from peat. Both Varadachari *et al*. (1991) and Yamaguchi *et al*. (2004) demonstrated that humic substances bond more effectively with 2 : 1 clay minerals such as smectite than with 1 : 1 clay minerals such as kaolinite because of the greater surface charge of the 2 : 1 minerals. The research therefore indicates that before humic substances are applied in an effort to improve soil structural condition, the soil mineral suite should be characterised to ensure that the amendments are effective for this purpose.

Spark *et al*. (1997*a*) found that positively charged exchange sites on soil mineral surfaces form stronger bonds with humic acids than negatively charged sites, but that the bonding potential depends on the pH, mineral suite, and electrolyte concentration in the surrounding soil. As a further example of the aggregating potential of humic substances, Imbufe *et al*. (2005) successfully used a commercially available product, K-Humate®, at a rate of 1.0 g/kg in a dispersive sodic soil and 0.05 g/kg in an acidic soil, to improve structural condition. The resilience of humic substances may enhance their ability to maintain soil structure compared with synthetic soil conditioners, which are susceptible to microbial decay (Albiach *et al*. 2001; Imbufe *et al*. 2005).

As biomass from cropping systems becomes more widely used in the production of bioenergy, there will be greater pressure on farmers to harvest crop residues that may otherwise have been maintained to reduce soil erosion, increase soil organic matter, and improve soil surface condition (Johnson *et al*. 2004). The use of bioenergy production waste materials as OA to improve soil structural condition may reduce the impact of harvesting the stubble as a source of biomass. Johnson *et al*. (2004) found that the byproduct of corn stover fermentation, which has a lignin content of ~70%, increased the stability of air-dried aggregates in a highly erodible soil by >5%. As Taheripour *et al*. (2010) suggests, returning residues from bioenergy production to agricultural land from which feedstock biomass is harvested may help alleviate soil health issues that arise from the removal of this material, thus improving the efficiency of the system.

The ability of OA to maintain and improve the physical condition of soil was also identified by Clark *et al*. (2009), who applied lucerne pellets, green wheat shoots, canola and chickpea stubble, chicken manure, peat, and sawdust in an effort to ameliorate the structural stability of a sodic (exchangeable sodium percentage >20%) clay soil. Application of low C/N ratio OA (wheat shoots and lucerne pellets) caused the rapid formation of water-stable macro-aggregates (>2 mm) in the soil, whereas the formation of water-stable macro-aggregates was significantly slower when higher C/N ratio OA (crop stubble) was applied. Clark *et al*. (2009) concluded that the speed with which the microbial populations utilised the OA as a source of energy was correlated with the rate of formation of the aggregates in the soil. However, their findings also indicate that there may be a point where the C/N ratio is too high for microbial species to effectively utilise an OA, as soils amended with sawdust and a peat showed an insignificant change in the amount of water-stable aggregation.

Microbial exudates from a variety of species have been found to significantly influence soil aggregation (Guggenberger *et al*. 1999; Preger *et al*. 2007). The quality of these substances can be manipulated via the addition of food or energy sources to the environment surrounding the microorganisms responsible. For example, Engelking *et al*. (2007) used two different forms of sugar, cellulose and sucrose, to study changes in bacterial and fungal communities in the soil. The quality of the food source provided to the soil microbial populations influenced the composition and quality of residues and exudates produced by the microorganisms. The addition of sucrose, considered a high-energy food source for microbial species, resulted in a high C/N ratio in exudates formed in the soil (Engelking *et al*. 2008). A high C/N ratio is likely to increase the resilience of these substances to biochemical breakdown, thus enhancing their longevity in the soil. Products such as fish hydrolysates and MBBM, which have been shown to stimulate microbial activity (El-Tarabily *et al*. 2003; Cayuela *et al*. 2009), may lead to improved soil structure

as they are likely to have some effect on the exudates and residues produced by microorganisms. However, there is little research that has investigated the potential of these OA for this purpose.

### *Use of organic amendments in management of contaminated and degraded soil*

Organic amendments have been successfully used in the remediation and stabilisation of contaminated and degraded soils around the world. In particular, OA have been applied to reduce the bioavailability of heavy metals (Hettiarachchi and Pierzynski 2004; Knox *et al*. 2006; Chrysochoou *et al*. 2007) and pesticide and chemical residues (Si *et al*. 2006; Dercová *et al*. 2007; Burns *et al*. 2008), and to improve the physical and chemical attributes of degraded agricultural soil (Imbufe *et al*. 2005; López-Piñeiro *et al*. 2007).

The mobility and bioavailability of heavy metals in soil have been reduced through the addition of humic substances (Misra *et al*. 2009). The efficiency of humic substances in forming metal–humic acid complexes depends on the mineral suite of the soil, as competition exists between the soil minerals and heavy metals for the bonding sites on humic substance (Spark *et al*. 1997*b*). This competition was identified by Wang *et al*. (2000), who found that ionic strength, pH, and the concentration of humic substance all greatly influenced the bonding between it and the lanthanide elements europium and ytterbium. Clemente and Bernal (2006) were able to reduce the mobility of both zinc and lead in an acidic soil via the addition of a humic substance, but noted a slight increase in the mobilisation of iron and copper in the treated soil. They also noted that the effect of the humic substance was far less significant in calcareous soil, further illustrating the importance of soil pH and ionic strength on the efficacy of OA in remediation and stabilisation of pollutants.

Several studies have also utilised MBBM to reduce the bioavailability of heavy metals in soil, particularly lead (Sneddon *et al*. 2006; Chrysochoou *et al*. 2007; Deydier *et al*. 2007). The use of MBBM and other amendments containing relatively high phosphorus concentrations (Table 2) can effectively immobilise lead in contaminated soil (Hettiarachchi and Pierzynski 2004). Deydier *et al*. (2007) showed that the application of MBBM ash, as a source of phosphorus, immobilised lead in solution, thus reducing its bio-availability. In a column leaching study, Sneddon *et al*. (2006) found that the addition of MBBM product to columns containing contaminated soil significantly decreased the leaching of lead, cadmium, and zinc. Sneddon *et al*. (2006) cautioned, however, that on-going application of the OA would be required, as mineralisation and weathering of the metal–amendment complexes would ultimately result in the remobilisation of the contaminants.

Pesticides and their residues can pose potential environmental risks if they remain active in the environment. Dercová *et al*. (2007) found that humic substances extracted from lignite significantly reduced the mobility of pentachlorophenol (PCP), a substance of high toxicity to humans and animals that has been banned in several European nations and is subject to restrictions as defined in the Rotterdam Convention (FAO and UNEP 1996), to which the Australian Government adheres (DAFF 2009). Dercová *et al*. (2007) used a humic substance–zeolite organomineral complex to form bonds with PCP molecules, successfully reducing its bioavailability, but noted that with time these bonds weakened and broke through weathering and decay, releasing this pollutant back into the environment. In another study examining the environmental risks associated with pesticides, Burns *et al*. (2008) investigated the complexation characteristics of humic substances in composted cotton gin trash as a potential method of reducing the bioavailability of endosulfan sulfate and diuron in irrigation tail waters. They found that the sorption of the pesticides to the humic substance reduced their solubility and removed them from the irrigation water, thus minimising their environmental risk.

Acidic soils can have a detrimental effect on plants and soil biota by increasing the mobility of toxic ions. Peiris *et al*. (2002) found that addition of calcium-rich humic substances derived from brown coal was more effective than lime ($CaCO_3$) in reducing the mobility and alleviating the toxic affects of aluminium in acidic soil. Applications of lime and gypsum ($CaSO_4.2H_2O$) are used to manage acidic soils in Australia, reducing the mobility and toxicity of aluminium and manganese species (Smith *et al*. 1994). Peiris *et al*. (2002) suggested that the application of a fulvate-rich (~50% fulvic acids) humic substance is an alternative that may provide a more sustained benefit than lime.

Much of the research on the application of OA to manage contaminated soils has focused on immobilisation and reduction of bioavailability, rather than the removal of pollutants (Bolan and Duraisamy 2003). Degradation or changes in the state of OA used in this form of soil remediation must be well understood to ensure that the pollutants do not remobilise in the soil (Bolan and Duraisamy 2003). For example, the solubilities of humic substances should be considered when they are being utilised to reduce the mobility of heavy metals, as the ability of humic substances to immobilise heavy metals has been shown to depend on pH. Therefore, if the pH of a soil changes, the solubility of the humic substance also changes, and concurrently the bioavailability of the contaminants. Kumpiene *et al*. (2008) concluded that a range of OA are capable of reducing the mobility of arsenic and heavy metals in soil, but advised that the choice of amendment would depend on the contaminant type and a range of soil properties, including clay content, pH, and the amount of humified organic matter present in the soil. Environmental factors such as soil moisture and temperature should also be considered, as they are likely to affect the mineralisation rate of OA in the soil (Ahn *et al*. 2009), and thus the longevity of any benefits provided by their application.

While the stabilisation of soil contaminants *in situ* is a legitimate management approach, a more permanent method, where circumstances allow, is via phytoremediation. This method relies on the ability of some plants to accumulate heavy metals in their biomass, which is then harvested, thus removing pollutants from the soil (Nedelkoska and Doran 2000). Several studies have been conducted exploring the possibility of using bio-inoculants to enhance the performance of plant

species for phytoremediation. Dell'Amico *et al*. (2008) inoculated a cadmium-contaminated soil with various rhizobacteria that produce the growth-promoting hormone IAA. The treatment led to an increase in the biomass of canola. Although cadmium accumulation was not enhanced in terms of percentage dry-weight, there was an increase in the amount removed from the soil due to greater total dry-weight biomass. Göhre and Paszkowski (2006) suggested that arbuscular mycorrhizal fungi may increase the rate of phytoremediation by enhancing the ability of plants to extract heavy metals from the soil. Arbuscular mycorrhizal fungi are also capable of acting as bio-protectants, insulating plants from toxic compounds and heavy metals (Jeffries *et al*. 2003). Bio-inoculants can potentially improve the efficiency of remediation and stabilisation of contaminated soils, economically and safely.

## Current limitations to the adoption of OA and their future in Australia

The hitherto slow adoption of OA in Australian broadacre agriculture can be attributed to factors such as a lack of unbiased scientific information on their agronomic utility in this agricultural sector, high rates of application required to ensure benefits, product variability, and public perception. Despite the low levels of OA utilisation, some of these products can sustain and enhance the health of agricultural soils (Bulluck *et al*. 2002); they may provide alternative and renewable sources of nutrients and, in some cases, improve the economic and resource efficiency of industries, governments, and municipalities by reducing and recycling waste materials that would otherwise be disposed to landfill. There is also evidence that OA can assist in managing agronomic pests and diseases (Rotenberg *et al*. 2005; Spadaro and Gullino 2005), improve the performance of synthetic inputs (Chan *et al*. 2007*b*), and reduce greenhouse gas emissions from agricultural soils (Lehmann 2007).

While a significant body of research investigating the use of OA has focused on horticultural crops, there is limited scientific information on their potential application in broadacre agriculture (Table 3). Several factors have stifled research efforts in this area since the end of the 19th Century. Initially, the introduction of inorganic fertilisers and pesticides allowed farmers to move away from organic inputs, which turned the focus of agricultural research towards understanding how best to utilise these new synthetic alternatives; this research is on-going (Cassman *et al*. 2009; Li *et al*. 2009). In the mid 20th Century, the Green Revolution saw the introduction of rice and wheat varieties bred to produce large yields in response to the application of synthetic fertilisers (Khush 1999). These events reduced the level of interest in, and need for, organic inputs in agriculture.

The lack of scientific information on the application of OA in broadacre agriculture can also be attributed to the inconsistent composition of some products and the high application rates required for beneficial outcomes. As Edmeades (2002) identifies, there has been large variation in the findings of research on the utilisation of OA, some of which may be explained by the inconsistency of product composition. For example, Hargreaves *et al*. (2009*b*) applied a municipal solid waste compost product in two successive years where the N-P-K concentrations of the product changed from 18, 0.4, and 10 g/kg in the first year to 23, 6, and 6 g/kg in the second year. Such inconsistencies represent a substantial challenge for researchers striving to predict confidently the effects of OA application to different agricultural systems. They are also likely to reduce the adoption rate of these products by farmers, due to the uncertainty in the agronomic utility of these amendments from one season to the next. Conflicting findings may also be a result of the heterogeneous nature of soils. Moisture content, temperature, microbial species, mineral suite, pH, texture, and OC content of soil have been shown to influence the efficacy of OA (Varadachari *et al*. 1991; Engelking *et al*. 2007). In research relating to the utilisation of soil-applied OA, the soil environment requires close investigation to ensure that the interaction of these products with their surroundings is well understood. Defining the properties and characteristics of soil that positively correlate with the application of these products will advance their utility and adoption.

The established benefits of some OA in horticultural systems are often realised only at application rates that may be considered uneconomical in broadacre farming (Table 3), such as 5 t/ha of MBBM applied by Mondini *et al*. (2008), or 5500 L/ha of swine manure applied by Lazarovits *et al*. (2001). There is, however, potential to reduce these rates through targeted and precise application. Technologies available in precision agriculture such as variable rate spreaders and soil injection may help reduce the amount of OA required per hectare. Some products, such as vermicomposts, humic substances, and seaweed extracts, are proven to be beneficial when applied at rates suitable for broadacre agricultural applications (Table 3). To enhance the rate of adoption of OA, a greater understanding of their capabilities and suitability is required, along with improvements in the consistency of their composition.

The public perception of OA, particularly the opinion of farmers, appears to be that these products lack unbiased scientific and experimental field-based evidence as to their efficacy. In a survey of Australian cotton farmers, Shaw (2005) found that 76% of those surveyed were cautious of soil health products, including seaweed extract, humic substances, and bio-inoculants. The farmers suggested that the promotion of these products tended to rely on anecdotal evidence and had 'no scientific foundation that they could see'. The report compiled by Shaw (2005) illustrates that further scientific investigation will potentially benefit both farmers and the manufacturers of OA.

Over thousands of years, organic materials have been used successfully to maintain crop yields and the health of soils, and to manage agronomic pests and diseases, supporting agriculture without the reliance on fossil fuels and external inputs of contemporary conventional farming practices (Pimentel *et al*. 2005). However, due to the increasing demand for food of the world's population, we conclude that OA are unlikely to ever replace, or become more common than, inorganic inputs. As Pimentel *et al*. (2005) suggests, it would seem more likely that a wide range of organic products will be gradually integrated into modern agriculture to help improve and sustain these production systems.

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