Compost as a valuable tool for improving the sustainability of rainfed cropping systems

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Abstract

Agriculture is faced with an expanding human population that requires feeding with a limited amount of resources. It is essential to find ways to be more efficient with non renewable fertiliser inputs. Compost presents a valuable tool for increasing the sustainability of rainfed cropping through recycling nutrients, improving water and fertiliser use efficiency and suppressing plant pathogens. Compost is a complex organic substance, with a plethora of modes of action. There are difficulties in transport costs for the rates generally suggested in the literature, but these may be overcome through novel techniques for precision placement of compost in the crop root zone.

Introduction

The expanding human population presents the agriculture sector with a monumental challenge. By 2050 there will be at least twice as many people as there were in 1980 (United Nations, 2004, Beddington, 2010). These people must be fed from existing farmland, much of which is degraded (Borlaug et al., 1982) and at risk of further degradation through climate change (Garnaut, 2008, Stern, 2007, Ingram et al., 2008). The population increase to current levels has been supported by significant improvements in crop yields as a result of the varieties and techniques developed in the green revolution (Quinn, 2008, Reynolds and Borlaug, 2006) . These high yields are dependent upon the use of crop cultivars that respond to high levels of fertilisers (Khush, 1999), but the continued supply of these fertilisers is not guaranteed.

Phosphorus (P) fertiliser is refined from mined rock phosphate (UNIDO, 1998). Production from rock phosphate mines will peak soon if it has not already. Lower quality ores and a reduction in the supply of new deposits will impede further extraction (Beardsley, 2011, Cordell et al., 2009, Dery and Anderson, 2007). Nitrogen (N) fertiliser is made from N_2 gas extracted from the air. This is an entirely renewable source, however the process involves the use of fossil fuels (mainly methane/natural gas) as hydrogen donors and to heat and pressurise gas in the manufacturing process (UNIDO, 1998). Until large scale investments in renewable sources of energy and hydrogen are made N fertiliser costs will follow the price of increasingly expensive fossil fuels (Shafiee and Topal, 2010). In many ways fertiliser inputs are becoming scarcer and more costly, while the necessity for them is increasing.

There are three methods for meeting demand for nutrients into the future; 1) discovering new sources, 2) improving the efficiency of existing resource usage, and 3) recycling nutrients to form a closed loop from paddock, to plate, to paddock (Beddington, 2010, Berg et al., 2005). It is unlikely that we will continue to find cheaply extractable and processable deposits of nutrients indefinitely (Beardsley, 2011). New technologies may allow processing of seawater (Lee et al., 1992, Yamaguchi et al., 2004) or very low quality ores (Broska et al., 2004), but as yet these are both uneconomical and impractical. The most likely options for a sustained fertiliser supply for food production are improving efficiency (more yield of food per tonne of fertiliser) and most importantly, closing the nutrient loop between paddock and plate, removing the need for further mining (Beddington, 2010, Cordell et al., 2009, Berg et al., 2005).

Good quality compost possesses a suite of attributes for soil and plant health that allow plants to make efficient use of fertiliser. Additionally, it represents a path for returning nutrients in organic wastes from urban areas to farmland (Cordell et al., 2009, Quilty and Cattle, 2011). Qualities such as improving soil water holding capacity and reducing fungal disease increase plant yield by removing stresses. Properties such as increased mineralisation of nutrients, increased exchange capacity and increased availability of nutrients improve yield by allowing plants access to a greater proportion of fertiliser applied to the soil. The mechanisms by which compost allows greater production per unit of fertiliser applied to rain fed cropping systems will be the focus of this review.

Water

In rain fed cropping systems, such as the Western Australian wheat belt, the single most limiting factor to yield is water (Kim et al., 2003). Successful managers index their fertiliser inputs based on the amount of water provided by rainfall (Oliver and Robertson, 2009, French and Schultz, 1984), but there is always an element of uncertainty (Simpson et al., 2007). Crops with less than ideal access to water will not grow to their full potential (Donatelli et al., 1992, Norouzi et al., 2008). Consequently they are unable to use applied fertiliser to the same extent as they would with free access to water (Huang et al., 2007). Therefore, increasing the proportion of plant-available water in the soil could be a major factor in increasing the efficiency of fertiliser use.

Compost can increase the water holding capacity of soils via several pathways (Ojeda et al., 2010). Notwithstanding variations arising from different inputs and particle sizes, good quality compost can on average absorb 250% of its dry weight in water (~70% water content) (Zhu, 2006, Liao et al., 1993). This is however based on the water holding capacity (WHC) of the inputs, not the finished product. There are few examples of the WHC of finished compost available in scientific the literature. Consideration of compost WHC is made in terms of the ideal starting moisture of composting inputs to allow maximum biological activity balanced with maximum airflow during the composting process. There is little scientific attention paid to the finished moisture content, and even less to the water holding capacity (Zhu, 2006, Tiquia, 2005, Liao et al., 1993, Hubbe et al., 2010, Petric et al., 2009). Assuming the WHC of finished compost is at least as high the starting materials, a 5t ha^{-1}(dry weight) application would store 12,500 L of water ha^{-1} from each rainfall event (assuming compost drying between events, calculations in appendix 1). This is equivalent to storing 1.25mm of rain.

The physical absorption capacity of compost is secondary to the potential storage increases that can be gained by improvements in soil structure and health (Carter et al., 2004). Compost has been shown to increase soil biological activity (Borken et al., 2002, Saison et al., 2006, Cytryn et al., 2011, Vinhal-Freitas et al., 2010). Young and Crawford (2004) have suggested that soil biology is able to rearrange soil particles into an ordered structure. The new structure has a distribution of pore sizes that are able to hold more water against gravity, compared with unstructured soil. The structure also has a greater connectivity of pores, allowing both more even penetration of water from rainfall and greater access of crop roots to retrieve it (also known as hydraulic conductivity) (Hayashi et al., 2006, Bhattacharyya et al., 2006, Celik, 2009). Arbuscular mycorrhizal fungi (AMF) infection of crop roots is increased by compost application (Bilalis and Karamanos, 2010, Ishii et al., 2004, Hameeda et al., 2007, Larkin et al., 2011). AMF assist with forming soil structure, explore pore sizes too small for plant roots and significantly increase the total volume of soil explored for both nutrients and water (Garg and Chandel, 2010, Kaya et al., 2003, Al-Karaki, 1998, Rillig et al., 2003). Soil bacteria stimulated by compost exude polysaccharides that act as a glue to hold soil particles together to form a structure of water stable aggregates. AMF form a similar function with the exudation of the protein glomalin (Curaqueo et al., 2011, Wu et al., 2011, Valarini et al., 2009, Rillig et al., 2003). Their exudates can also reduce the adhesion of water to soil particles, decreasing the suction required for plants to extract water from soil pores, allowing access to a greater proportion of soil water (Martens and Frankenberger, 1992, Caesar-TonThat et al., 2007, Young et al., 1998, Kaci et al., 2005). Compost stimulates root growth (Bibi et al., 2010, Hameeda et al., 2007). Increased root growth leads to increased exploration of soil for water and also leads to increased root exudates, which further stimulates soil biology (Nardi et al., 2002b, Broeckling et al., 2008). Finally the humic fraction of compost (humates) increases the water use efficiency of plants. The mechanism is not yet well described, but involves humates entering the plant and influencing water regulation (Eyheraguibel et al., 2008, Morard et al., 2010). The combination of these factors leads to an increase in soil WHC above the absorption capacity of compost alone.

Despite widespread published data on the factors leading to compost increasing soil water holding capacity it is rare that the actual increase is reported. Where it is measured results have shown that high application rates in minimum tillage systems (which allow soil structure to build over multiple years(Triplett and Dick, 2008)) can lead to total improvement in WHC in the order of 50%. Mamo et al (2000) published findings that equated to a maximum of 50% increase in WHC at 10-20cm when applying 270 t ha^{-1} of municipal waste compost. Although WHC increased, plant available water decreased in some situations. This was a consequence of large cation (Na^+ and Ca^{2+}) increases causing physiological drought for plants. Barzegar et al. (2002) reported an overall increase in soil WHC, but noted the increase was only in the -10 kPa (field capacity) to -100 kPa matric potential range. There were no improvements in WHC from -100 to -1500 kPa (wilting point). When using the lower rates suggested for broadacre rainfed cropping (rather than hundreds of tonnes ha^{-1}) (Quilty and Cattle, 2011) the literature indicates that the total contribution of compost to water holding capacity is ~10% (Fahmy et al., 2000, Bareja et al., 2010, Barzegar et al., 2002).

Increasing soil water holding capacity is of minor consequence in high rainfall zones where regular rain maintains soil moisture (Brisson et al., 2002). Increased soil water could be of greater consequence for rainfed cropping in medium and low rainfall areas, where soil undergoes wetting and drying cycles during the season (Sanger et al., 2010, Al-Karaki, 1998). At first glance it appears that increasing soil water holding capacity would be of greatest benefit to the driest cropping areas, as they have the most to gain (Sanger et al., 2010, Subramanian and Charest, 1999). This is difficult to verify via the scientific literature, as comparisons have not been made for soil WHC between climate zones.

A simple model can be used to test the hypothesis that water holding increases from compost would be of the most benefit to the driest cropping areas. Crop plants in a mid to low rainfall zone could potentially suffer water stress several times in the growing season when the period between rainfall events is longer than stored soil moisture can supply the plants (Sanger et al., 2010, Norouzi et al., 2008). Rainfall data from a range of Western Australian cropping locations (Australian Bureau of Meteorology long term rainfall averages for Southern Cross, Merredin, York and Katanning) shows that lower rainfall areas experience a longer interval between >10mm rainfall events than high rainfall areas. The assumptions are made that all rainfall events are sufficient to reach field capacity, and that a 10% increase in soil water holding capacity would manifest as a longer period between rainfall and the onset of water stress for the crop (Kumar et al., 2006), Soil water holding capacity varies with soil type (Lugato et al., 2009) therefore a range of soil drying periods are used.

Figure 1 shows the model results in terms of the percentage decrease in crop water stress that compost application can provide. For all soil types, the greatest improvement was shown when rainfall intervals only partially exceeded the soil drying period. The relative gains decrease the longer the period of water stress. This implies that the greatest response to compost application is likely to be observed in the mid range rainfall zones rather than low rainfall areas where there are longer periods of water stress between rainfall events. This may point towards compost becoming less effective as climate change progresses. Rainfall has both been observed to not only decrease in the rainfed cropping areas of South-West Western Australia but also for rainfall events to be more intense and widely spaced in time. This trend is expected to continue (Yu and Neil, 1993). The increases in hydraulic conductivity of soil from compost application (Celik, 2009) may prove to be of greater importance than an increase in total storage in this scenario. This would be through increasing the amount of water that penetrates into the soil during intense rainfall rather than being lost as surface runoff.

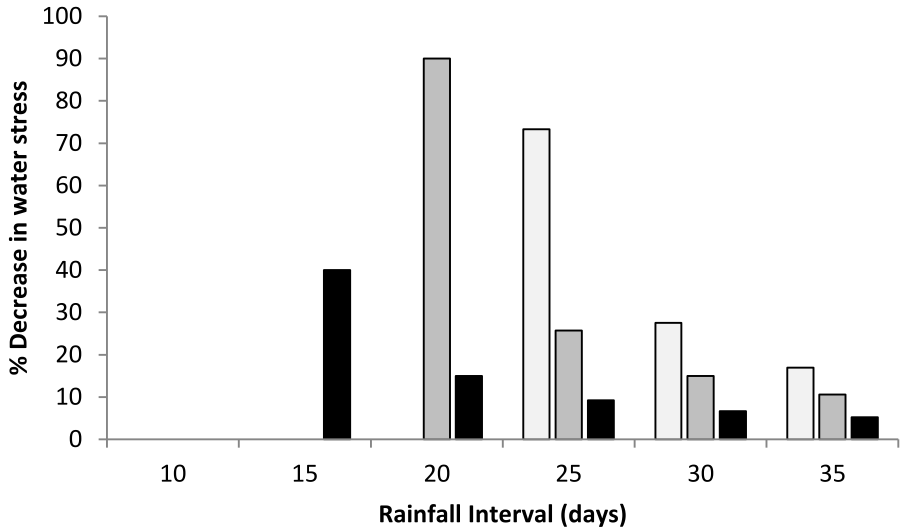

Figure 1: Percentage that compost application reduces water stress compared to conventional methods. The X axis represents the number of days between rainfall events. Black bars represent free draining soils that will cause plant water stress 12 days after rain, dark grey bars indicate soils that dry in 18 days and light grey bars denote soils that dry in 22 days. Bars are absent where there was no water stress.

Nutrient provision

The nutrient provision mechanisms of compost share some pathways with water provision. Compost application improves AMF infection of roots for most crops (Ishii et al., 2004, Bilalis and Karamanos, 2010). AMF increase the explored volume of soil by orders of magnitude and supply plants with nutrients (particularly P) in exchange for photosynthates (Hodge et al., 2010, Garg and Chandel, 2010). Compost also stimulates crop root growth, again increasing the surface area for absorption and the volume of soil explored (Bibi et al., 2010, Hameeda et al., 2007). Compost raises soil pH, which can help reduce acidity problems and raise pH to a point where nutrients are in more available forms (Slattery et al., 2002, Hoare, 1992). The stimulation of soil biology by compost increases the rate of nutrient cycling, generally leading to an increase in mineralisation of nutrients. As a result a greater proportion of the soil's nutrients are available to the crop (Cytryn et al., 2011, Saison et al., 2006, Tejada et al., 2006).

Humates are involved in water use efficiency in plants internally, and also contribute to nutrient provision from outside of the plant (Morard et al., 2010, Gerke, 2010). Humates are large and complex molecules of humic acids which are the result of microbial decomposition of organic matter (Scott et al., 2001). Their complex but stable chemistry leads to a number of soil health benefits, including stimulation of root growth (Arancon et al., 2006, Chen et al., 2004) and an increase in exchange capacity of the soil (particularly important in sandy or calcareous soils)(Garcia-Mina et al., 2004). One of humate's most important benefits to rainfed cropping in P deficient landscapes, such as Western Australia, is in their associations with P (Lambers et al., 2010, Gerke, 2010).

Humates store P in the soil in a manner that is both available to crop plants and resistant to leaching (Gerke, 2010). P in the soil solution does not bind directly to humates, but will form a complex with metals (particularly aluminium (Al) and iron (Fe)) bound to the humate surface (Yamamoto et al., 2010, Gerke, 1994). These are known as humic-metal-P complexes (HMEP)(Gerke, 2010). HMEPs provide a mechanism to retain P added as fertiliser so that it is neither leached through the soil profile beyond crop roots, nor adsorbed to clay colloids and hence irretrievable to most plants (Gerke, 2010). P bound to HMEPs is not directly available to most plants either, but strategy II Fe acquisition plants (cereals) are able to mobilise Fe from humates by exuding phytosiderophores (Romheld and Marschner, 1986). In the process P desorbed from Fe and enters the soil solution where it can be taken up by the crop (Gerke, 2010, Gerke, 1995). Some leguminous crops and pastures such as *Lupinus albus* and *Trifolium pratense* are able to mobilise P directly both from HMEP and clay colloids through the exudation of citrate and could be useful as companion crops for non cereal crops (Zhu et al., 2005, Gerke and Meyer, 1995). Humates further reduce the amount of P locked up on the soil surface by competing with P for sorption points (Gerke and Hermann, 1992). Existing sorbed P can be displaced and then adsorbed as HMEP (Gerke, 2010). Humates are not only involved in P provision. They also improve plant nutrition through increasing the availability of both macro and micro nutrients through similar mechanisms to HMEPs (Marino et al., 2008). This appears to be of particular significance where there are crop deficiencies in micronutrients such as Fe, Cu and Zn either through low soil concentrations or chemical unavailability (Garcia-Mina et al., 2004, Lua and Bohme, 2001, Verlinden et al., 2009, Tahir et al., 2011).

Humates have a further nutrient provision role within the plant. They are said to affect the function and physiology of plants in ways that improve the uptake of nutrients (Trevisan et al., 2010a, Eyheraguibel et al., 2008). This is suggested to be through hormone mimicking effects of humates but Chen et al. (2004) proposed that the observed growth effect may be due to micronutrient provision from humates rather than hormones. There is a large body of evidence that rejects this and shows that auxin and other hormone receptors are being stimulated (Debi et al., 2005, Nardi et al., 2007, Morard et al., 2010, Sessi et al., 2001). This stimulation results in a range of changes in the plant including increased root hair numbers and branching of roots (Trevisan et al., 2010b, Debi et al., 2005). The hormonal effects are associated with a particular molecular size fraction of less than 3.5 kDa (Nardi et al., 2002a). This size fraction is both small enough to pass through the cell wall and interact with the plasmalemma (Muscolo et al., 2007, Morard et al., 2010, Nardi et al., 2002a) and has a different structure to larger fractions. Below 3.5kDa humates are characterised by aliphatic structures, while above 3.5 kDa there is a greater prevalence of aromatic structures (Muscolo et al., 2007, Ferrari et al., 2011).

There appears to be some confusion in the literature as to when humate related growth improvements should be attributed to hormone like effects or humate's properties in the soil. For instance Vlckova et al. (2009) found that a larger humate fraction of 35-175 kDa resulted in the highest growth in maize (*Zea mays*) rather than the <3.5 kDa fraction. It may be that the 35-175 kDa fraction is the most effective at improving the availability of nutrients in the soil, but it is difficult to clarify why one study finds <3.5 kDa to be the most effective (Nardi et al., 2007) and another says 35-175 kDa produces the greatest plant growth for the same species (Vlckova et al., 2009). Studies of the activity of genes activated by hormones are providing some clarity (Trevisan et al., 2010b, Debi et al., 2005), but experiments where humates are present only in the plant or the soil and excluded from the other are needed. Careful management of compost applications to crops may be required in order to achieve the best results. Both (Tahir et al., 2011) and (Pinheiro et al., 2010) reported that high doses of humates were less beneficial than lower doses. Pinheiro in particular reported that a very low dose of 0.07-4.3 mg L^{-1} resulted in the highest plant growth. Humate applied as compost presents a range of factors to consider in calculating dosage (e.g., EC and nutrient content) and at the farm management level a degree of trial and error may be required.

AMF stimulated by compost can provide improvements to nutrient uptake when in symbiosis with plants (Garg and Chandel, 2010). AMF are well known to improve the efficiency of plant P uptake and a range of other nutrients, including organic N (Al-Karaki, 1998, Subramanian and Charest, 1999). The level of benefit to plants from AMF is most commonly reported as the percentage of root area infected (Bilalis and Karamanos, 2010, Ishii et al., 2004, Hameeda et al., 2007, Larkin et al., 2011). This is the simplest proxy used to quantify an increase in the interaction between AMF and the host plant, but it is not necessarily accurate (Lekberg and Koide, 2005). The symbiosis between plant and AMF can range from mutually beneficial to parasitic (Jakobsen et al., 2002). Where P is not limiting an increase in AMF infection can lead to a reduction in growth from an increased cost in photosynthate to the plant for little return from the fungi (Jakobsen et al., 2002, Graham, 2000). An equal increase in AMF infection when P is limiting can result in strong increases in growth (Ryan et al., 2000). The simple reporting of the percentage of AMF infection of plant roots provides little information as to the health of the host plant (Lekberg and Koide, 2005, Jakobsen et al., 2002). The measurement remains the most prevalent as more accurate measurements are expensive and time consuming (e.g. introducing labelled P into the soil), particularly where AMF are not the focus of the study (Lekberg et al., 2010). However, correlation of plant growth, plant tissue concentrations of nutrients and AMF infection could provide criteria for assessing if changes in AMF infection are beneficial to the plant.

Disease suppression

The disease suppression properties of compost in rain fed cropping are not well studied, but have been widely studied in horticulture (Braun et al., 2010, Scheuerell and Mahaffee, 2002, Krishna et al., 2010, Zhang et al., 1996). As in water and nutrient supply, there is no one factor responsible for the end effect of a healthier plant (Zinati, 2005). One of the most consistent disease control effects seen from compost application is suppression of fungal pathogens (Zhang et al., 1996, Ntougias et al., 2008, Zinati, 2005). This is not only for soil borne fungal pathogens, compost also controls some foliar infections (Scheuerell and Mahaffee, 2002, Bailey and Lazarovits, 2003). Suppression can happen through introduction or stimulation of existing microbes antagonistic towards fungal pathogens (such as Trichoderma species)(Krishna et al., 2010, Alfano et al., 2007, Bailey and Lazarovits, 2003, Leandro et al., 2007), improvement of plant nutritional status (generally through supply of limiting micronutrients) allowing the plant to better resist attack (Bareja et al., 2010, Braun et al., 2010), and induced resistance (stimulating the plant to activate defences)(Ntougias et al., 2008, Yogev et al., 2010, Zhang et al., 1998). In horticulture, compost teas (liquid compost extracts) applied to plant canopies have a further suppressive effect on foliar fungal diseases (Zhang et al., 1998, Scheuerell and Mahaffee, 2002). Specific to rainfed cropping, compost has been shown to suppress the fungal infection take all in wheat (Tilston et al., 2005), and has suppressed anthracnose in bean and pea crops in a way that will also likely be relevant to lupins (Stone et al., 2003, Zhang et al., 1996).

Ammonia toxicity from the volatilisation of nitrogen controlling soil pathogens has been noted (Bailey and Lazarovits, 2003), but is mainly only seen at high application rates of poorly composted material, and could have detrimental effects to crop seedlings in a similar fashion to urea fertiliser sown too close to wheat seedlings (Zhang and Rengel, 2003). This effect could account for suppression of plant pathogenic nematodes occasionally seen (Nahar et al., 2006), although there are other potential mechanisms. These include compost borne bacteria which exude siderophores that immobilise Fe and induce deficiency in other species (Leong and Neilands, 1981). There may be mechanisms other than ammonia toxicity for nematode control. McSorley and Gallaher (1996) used very high applications of compost (269 t ha^{-1}) to achieve plant pathogenic nematode control in maize, but found that the greatest control of nematodes came in the third year of the trial. Ammonia toxicity resulting from low maturity compost would be expected to happen early in the first season as excess N is volatilised (Haden et al., 2011, Hayashi et al., 2009, Yan et al., 2001). Not all species of nematodes were controlled, pointing to a possible biological control. AMF have a suppressive effect on sedentary plant feeding nematodes and the stimulation of AMF by compost may be responsible for the observed suppression (Borowicz, 2001, Lax et al., 2011)

Problems with compost

In rainfed cropping, applying compost for a significant source of macronutrients would only be considered viable for organic agriculture (Conyers and Moody, 2009). The rates required to supply full nutrition to crops are a minimum of 10 t ha^{-1} (Celik, 2009, Quilty and Cattle, 2011), and the transport costs of this alone make it difficult for compost to compete with the cost of chemical fertilisers. A typical total application of fertiliser in the Western Australian wheatbelt could be up to 200kg total fertiliser applied (approx. 100kg of a fertiliser containing multiple nutrients (e.g. Di-ammonium phosphate (DAP)) and approx 100kg urea) (Simpson et al., 2007, Oliver and Robertson, 2009). Using a nominal transport distance of 200km and transport quotes from Custom Composts, Mandurah (Pers. comm. Jessica Bell, 2011) 10 t ha^{-1} of compost would cost \$112 (all quoted figures are in AUD) ha^{-1} to deliver, while 0.2 t ha^{-1} would cost \$2.24. Using good quality compost at \$55 m^{-3} and DAP at \$1000 t^{-1} and urea at \$800 (Custom Compost premium compost quote (Pers. comm. Jessica Bell, 2011) and February 2009 fertiliser prices from the Australian Senate Select Committee on Agricultural and Related Industries website http://www.aph.gov.au/Senate/committee/agric_ctte/fertiliser/report/c02.htm) the total cost for compost is \$958 ha^{-1} and fertiliser \$182 ha^{-1} (delivered to the farm, excluding spreading costs). Use of compost as a full replacement for fertiliser is unlikely to be economic in rainfed agriculture at these prices. An alternative is to compost on farm, which is possible but requires skill and attention to do well (Gagnon et al., 1999).

Skill and attention is also required in choosing a compost. There is a huge range of ingredients that can be used to make compost, including manures, municipal green waste, human waste (biosolids), animal carcasses, woodchips and cooking oils (Quilty and Cattle, 2011, Al Naddaf et al., 2011, Bastianoni et al., 2002, Cotxarrera et al., 2002, Fahmy et al., 2000, Kriipsalu and Nammari, 2010). Add to this variability in composting methods that can lead to differences in humate content (Zhu, 2006, Roca-Perez et al., 2009), and it becomes difficult for farmers entering the market to choose an appropriate compost (Quilty and Cattle, 2011).

The quoted humate content of compost can potentially be misleading. The total humic acid content is generally the figure quoted for particular composts (Quilty and Cattle, 2011) but as described in the 'nutrient provision' section of this review, different fractions of humates have different properties (Nardi et al., 2002a). A compost predominated by the low weight fraction of humates will have different results when applied to a crop than a compost predominated by high weight humate fractions (Morard et al., 2010, Vlckova et al., 2009), even if the total humates contents are the same.

Recycled organic wastes used in composts, particularly biosolids, can have levels of heavy metals that pose a risk of soil contamination (Smith, 2009). Tejada and Gonzalez (2007) showed that applying uncomposted biosolids had a negative growth effect on wheat and reduced soil biology as a result of heavy metals. Applying composted biosolids (or other inputs high in heavy metals) however showed up only one negative result due to heavy metals in Smith's (2009) review of composting of recycled organics. The process of aerobic composting complexes heavy metals in a way that makes them unavailable to soil biology or plants, removing the risk of application (Ho et al., 2010, Tiquia, 2010, Dumontet et al., 2001). The effect appears to be long lasting, to the extent that compost is used to filter metals from stormwater (Khan et al., 2009), neutralise industrial wastes by composting (Odlare and Pell, 2009, Ho et al., 2010) and to remediate contaminated soils (DeVolder et al., 2003). There is still the risk of poorly composted recycled organics causing heavy metal contamination. The negative result in the Smith (2009) review was the result of poor composting methods not providing sufficient aeration and producing a compost that has not completed the aerobic microbial digestion of the compost ingredients (i.e. the compost is not mature). Lack of aerobic conditions means a reduction in the complexation of metals (Dumontet et al., 2001). If a maturity index is not supplied for a purchased product, or for a farm manager not well versed in the risks of compost buying a low maturity compost based on cost savings, there is a significant risk of negative crop effects from heavy metals.

High application rates of compost can lead to problems with soil salinity. High soil EC brought on by the high levels of cations in compost (e.g. Na^+ and Ca^{2+}) can lead to physiological drought for plants and soil organisms causing reductions in yield and soil biological activity (Roca-Perez et al., 2009, Aoyama et al., 2006, Hurisso et al., 2011, Martin et al., 2011). Lower applications did not appear to cause any salinity problems (Hurisso et al., 2011). It also appears that salinity may be a problem mainly with less mature composts. Tejada et al. (2006) found salinity problems with application of uncomposted beet waste, but found no ill effects when the waste was composted before application. Slattery et al. (2002) suggests that Na^+ is complexed by compost and made bio-unavailable. Salinity problems observed in the literature may be the result of incomplete composting or high Ca^{2+} levels in compost (Aoyama et al., 2006).

There is mixed evidence on the effect of compost on weeds. Various papers report both suppression of weeds (Brown and Tworkoski, 2004, De Cauwer et al., 2011) and promotion of weeds (Amisi and Doohan, 2010, Blackshaw et al., 2005). There is a risk of compost made from green waste spreading weed seeds and plant propagules, particularly those that are heat resistant (Tymms et al., 2011, Dorahy et al., 2009). Careful turning of windrows to ensure heat treating of the entire mix and sufficient heat and duration of composting are required to reduce this risk (Tymms et al., 2011, Dorahy et al., 2009). Promotion of weeds seems to be as a result of provision of nutrients (Blackshaw et al., 2005) or possibly weed seed spread (Tymms et al., 2011). Weed suppression may be through the action of Trichoderma species introduced by compost (Javaid and Ali, 2011) or suppression of weed seed germination (De Cauwer et al., 2011).

High levels of compost application present a risk for eutrophication (Martin et al., 2011, Tejada and Gonzalez, 2008). Composting reduces the risk of eutrophication compared to raw inputs (Banar et al., 2009). However, compared to an untreated soil compost can increase nutrient mineralisation (Cytryn et al., 2011, Saison et al., 2006). This increases the possibility of nutrients in the soil solution being leached into water bodies, particularly when the application rates are high (Martin et al., 2011).

How to make compost viable for rainfed cropping

Compost is unlikely to be taken up in rainfed cropping areas when application rates are high and transport costs are significant as demonstrated in the 'problems with compost' section of this review. Compost must be either competitive in price, or produce sufficient increases in yield to justify the cost. One method that may make compost in rainfed agriculture is to find ways of reducing the required compost application rate.

The normal method for applying compost is to spread it on the surface. It is then either left on the surface or incorporated into the top layers of the soil (Stieg et al., 1997). This application method can result in large amounts of compost that don’t reach the target of the crop root zone (Cogger et al., 2008, Blackshaw et al., 2005). Incorporation brings the added problem of incompatibility with minimum tillage systems (Triplett and Dick, 2008). A potential solution is precision placement of compost in the soil. This would involve placing compost directly in the root zone, and not on the surface or between rows (Blackshaw et al., 2005). In this way a sufficient concentration of compost could be reached in the root zone with significantly less compost. Pelletising compost has been trialled across the world (Xiao et al., 2010, Yan et al., 2001, Valat et al., 1991), and several businesses are producing pelletised compost in Australia (Quilty and Cattle, 2011). This presents an opportunity to band compost at seeding using air seeding equipment.

With a row spacing of 22.5cm (commonly used in wheat crops in rainfed agriculture (Ali et al., 2010, Das and Yaduraju, 2011)) reducing compost application from the entire row width to an approximately 5cm wide band (at the same cm^{-2} density as a full surface application) in the root zone would reduce the per hectare application from 10 t ha^{-1} (the application rate required for full nutrition of a crop when spread on the surface (Celik, 2009, Quilty and Cattle, 2011)) to 2.2 t ha^{-1}. Using the criteria from the 'problems with compost section' of this review, this brings the cost of compost application down to \$211 ha^{-1}. This is potentially competitive with normal chemical fertiliser application at \$182 ha^{-1}. Changes in fertiliser prices could bring compost below the price of fertiliser. At November 2008 prices for DAP and urea (\$1500 and \$1000 t^{-1} respectively (Australian Senate Select Committee on Agricultural and Related Industries website http://www.aph.gov.au/Senate/committee/agric_ctte/fertiliser/report/c02.htm)) fertiliser would cost \$262 ha^{-1} to apply.

Compost application rates could be further reduced when applied by subsurface banding in the manner that fertiliser is in low tillage systems (Blackshaw et al., 2005). In addition to reductions by eliminating application between crop rows, incorporating compost into the soil improves the efficiency of N supply (Cogger et al., 2008). This is partly through reductions in loss of N from surface runoff (Gove et al., 2002) and may apply to other nutrients. This could allow a further reduction in compost rate for the same crop growth. The cost of transporting compost could also be reduced by decentralisation of professional compost production from major cities to regional areas (Zurbrugg et al., 2005).

Compost can be used not only as a replacement for chemical fertilisers, but as a compliment to them. There is a broad range of independent trials across varying soils, crops and climates that report maximum yield and crop growth when compost and chemical fertilisers are combined (Sarwar et al., 2008, Bibi et al., 2010, Farooq and Farooq, 2001, Ribeiro et al., 2010, Biswas, 2011, Montemurro et al., 2005, Shah et al., 2007, Irshad et al., 2002). Most of these papers described the best results when chemical fertilisers were reduced by 50% (Montemurro et al., 2005, Ribeiro et al., 2010, Biswas, 2011, Bibi et al., 2010, Farooq and Farooq, 2001, Shah et al., 2007, Irshad et al., 2002). The Bibi et al. (2010) experiment is particularly interesting in that it also reduced compost rates to match fertiliser based on N content. The equal greatest shoot and root weights were achieved with the combination of 50% of normal fertiliser and 50% of the compost required to provide sufficient N. There was no difference in yield between the 50% fertiliser/50% compost treatment and the 100% fertiliser/100% compost treatment. Irshad et al. (2002) and Shah et al. (2007) reported similar results. Continuing the above pricing comparisons, 50% fertiliser/50% compost would be the cheapest compost nutrient supply option so far, at \$197 ha^{-1}. Yield should also be increased over 100% fertiliser, Bibi et al. (2010) showed a 13% shoot growth increase for 50% DAP/50% compost as compared to 100% DAP and 51% shoot growth increase as compared to 100% urea.

It appears that sub surface banding of compost has not yet been reported in the literature. No papers were found that mentioned compost in conjunction with banding or other potential terms for accurate subsurface placement. Papers were found on subsurface banding of manures and biochar which support the concept of banding compost, but no direct evidence for banding compost (Blackwell et al., 2010, Solaiman et al., 2010, Watts et al., 2011, Patni et al., 2000). Further research is needed to confirm that compost banding is viable.

Conclusion

Reducing chemical fertiliser with no yield penalty is an exciting outcome of compost application. It presents the possibility of significantly extending the lifetime of fertiliser reserves (Thanh and Matsui, 2011). This is not a truly sustainable situation, but it does buy more time to find methods of fully recycling nutrients from paddock to plate to paddock. For now compost provides partial nutrient recycling, increases the efficiency of fertiliser applications, and helps to improve soil water holding to assist with adaption to new rainfall regimes. When used in conjunction with good soil preservation techniques such as minimal tillage systems (Triplett and Dick, 2008) compost provides a very powerful and sustainable management tool to potentially allow for the human population to reach its maximum and stabilise without collapsing the world’s agricultural ecosystems.

Appendix 1

Litres ha^{-1} for 1mm rain = 10,000

compost application (kg dry weight ha^{-1}) = 5000

max compost water holding (L ha^{-1}) = 5000 x 2.5 = 12,500

mm rain ha^{-1} stored in compost = 12,500 / 10,000 = 1.25

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