THE UNIVERSITY OF ADELAIDE

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COMPOST EFFECTS ON SOIL WATER CONTENT, PLANT GROWTH UNDER DROUGHT AND NUTRIENT LEACHING

Thesis submitted to The University of Adelaide in fulfilment of the requirements for the degree of Doctor of Philosophy

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Dedicated to my father Nguyễn Văn Tráng and my mother Đặng Thi Phượng

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ABSTRACT

Compost is increasingly used in agriculture as a soil conditioner and fertilizer to improve soil properties and crop production by replenishing soil organic matter and supplying nutrients and thereby improving soil physical, chemical and biological properties. However, little is known about the effect of compost on soil water content and plant growth under water deficit stressed condition and if clay added to compost or soil influences nutrient leaching from compost. This thesis includes pot, field and laboratory incubation studies with the following aims (1) to assess the effects of compost on water availability to plants and gas exchange under well-watered and drought stressed conditions, (2) to study the long term effect of mulched compost after a single application, (3) to compare effects of incorporated and mulched compost on soil water content, nutrient uptake and plant growth, and (4) to determine the effect of clay added to compost or sandy soil on nutrient availability and leaching.

To assess the effects of compost on plant growth under water-limiting conditions, two pot experiments were conducted; one with tomato and the second with capsicum.

Tomatoes (*Lycopersicon esculentum* L.) were grown in pots were grown in a sandy soil without or with mulched or incorporated compost from garden and food waste to assess water availability to plants and plant physiology under well-watered and drought stressed conditions. Both mulch and incorporated compost increased plant growth with the greater effect by incorporated compost, but only incorporated compost increased total available water and water available to plants. Compost did not affect gas exchange in well-watered and drought stressed conditions, but the incorporated compost increased the recovery of plants after drought by increasing photosynthesis and transpiration rate compared to the plants without compost or with mulched compost. This may be explained by the greater root length and mass of plants grown with the incorporated compost compared to the other compost

treatments.

Pepper (*Capsicum annuum* L.) plants were grown in pots in a silt loam which had received mulched compost once three years previously, and in a corresponding unamended control under (i) sufficient water supply and (ii) two transient drought cycles, separated by one week of sufficient water supply. Compost applied once three years previously increased soil organic C and total N, dry root mass and root length under well-watered and drought stressed conditions. The single compost application increased total available water, total water used and water availability to plants grown in well-watered condition, but did not affect gas exchange and had no effect on water use efficiency and the capacity of plants to recover after drought. As in the previous experiment with freshly applied compost, mulched compost applied once three years previously increased the ability of plants to take up water by stimulating root growth.

To investigate effects of compost on soil water content and plant growth under field conditions, compost from garden and food waste was incorporated or mulched in a vineyard (*Vitis vinifera* cv. Merlot) at a rate of 100 m^3 ha^{-1} with normal irrigation during spring and summer. The compost was applied three months before the start of the first soil water content measurement. Only mulched compost increased soil water content at 10 cm depth and the rate of photosynthesis per plant at flowering, pea sized berries and maturity (about 13 months after application). Compost amendment, particularly mulch, increased yield, specific berry weight, and leaf N and P concentrations, and reduced the number of chlorotic leaves at harvest. It can be concluded that mulched compost has a positive effect on grapevine yield and can be used as an alternative fertiliser for vines with no adverse effect on berry quality.

Incubation experiments were carried out to assess effects of clay addition to compost or sandy soil on nutrient leaching. In the first incubation experiment, a fine-textured soil (34% clay) was added at 5% or 20% (w/w) to compost and this mix was incorporated into a sandy

soil. Compost addition increased nutrient availability and leaching. Addition of the fine-textured soil to compost reduced nutrient leaching, especially N and P from compost. In a second incubation experiment, clays isolated from a surface soil and subsoil were added to a loamy sand (98.1 g clay kg^{-1}soil) and different concentrations of water-extractable organic C (WEOC) from compost was added. Clay addition reduced C loss (mg C per kg soil) via leaching and respiration and increased the WEOC sorption capacity of the loamy soil. The clay properties such as mineralogy, surface area, cation exchange capacity and exchangeable Ca concentration cannot explain differences in C sorption and loss. However, clays with a high C sorption capacity had low indigenous organic C and high Fe/Al concentrations. It can be concluded that clay addition to compost or soil reduces the risk of entrophication and increase C sequestration by decreasing C loss via leaching and respiration if the added clays have low total organic C and high Fe/Al concentrations.

DECLARATION

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Trung Ta Nguyen

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2. T.-T Nguyen, S. Fuentes, and P. Marschner. 2013. Growth and water use efficiency of *Capsicum annuum* in a silt loam soil treated three years previously with a single compost application and repeatedly dried. *International Journal of Vegetable Science* (In press). DOI:10.1080/19315260.2013.764508.
3. T.-T Nguyen, S. Fuentes, and P. Marschner. 2013. Effect of incorporated or mulched compost on leaf nutrient concentrations and performance of *Vitis vinifera* cv. Merlot. *Journal of Soil Science and Plant Nutrition*. **13**, 485-497.
4. T.-T Nguyen and P. Marschner. 2013. Addition of a fine-textured soil to compost to reduce nutrient leaching in a sandy soil. *Soil Research*, **51**, 232-239.
5. T.-T Nguyen and P. Marschner. 2014. Retention and loss of water extractable carbon in soils: effect of clay properties. *Science of the Total Environment*, **470**, 400-406.

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

Compost is defined as stable aerobically decomposed organic matter and results from a controlled decomposition process. Compost is widely used for agriculture and horticulture, especially for sandy soils because it not only reduces the amount of materials going to landfill, but also improves soil quality and crop production by providing organic matter and micro- and macro-nutrients. Landfill can lead to environmental problems because of chemical leaching and methane gas emission (Davoli *et al.*, 2003), and the presence of pathogens and toxins (Darby *et al.*, 2006). The methane emissions from landfills constitute about 30% of the global anthropogenic emissions of methane in the atmosphere (COM, 1996). This can be potentially detrimental to both local and global air quality (Allen *et al.*, 1997). Reducing the amount of methane emitted from landfills is considered to have the greatest potential of reducing the overall climate change impacts of waste management (Smith *et al.*, 2001).

Compost application results in a range of environmental benefits, including improved soil health, water savings, synthetic fertiliser reduction and improved crop productivity. The beneficial effects of compost on soils have led to an increase in usage together with or instead of chemical fertilizers (Davies *et al.*, 1972; Beyer *et al.*, 2002; Schroth *et al.*, 2003). Plants cannot utilise organic nutrients from compost directly for their growth, but organic matter from compost is a vital component from a soil fertility perspective as it improves soil aggregation, structural stability and water infiltration and provides nutrients after mineralisation (Aggelides and Londra, 2000; Schroth *et al.*, 2003; Tejada and Gonzalez, 2003). Compost contains large amounts of nitrogen and other nutrients in organic and inorganic forms (Paradelo *et al.*, 2007; Chamini *et al.*, 2008; Curtis and Claassen, 2009; Wang *et al.*, 2010). Compost has more advantages than other organic amendments because of reduced volumes and slower decomposition rate and absence of pathogens (Bernal *et al.*, 2009). The effect of compost on plant growth and crop production not only depends on nutrients from compost, but also be due to increased soil water content because compost application can reduce evaporation and erosion (Pinamonti, 1998; Arthur *et al.*, 2011). This leads to increased crop growth and yield (Levy and Taylor, 2003; Wang *et al.*, 2010). However, nutrients added with the compost may be lost via leaching (Shepherd and Bennett, 1998; Mamo *et al.*, 1999; Basso and Ritchie, 2005).

Composting has been primary concerns of all government jurisdictions and is an important alternative for recycling and diverting biodegradable waste. The amount of organic waste composted in the UK in 2004 - 2005 was estimated at 2.7 million tons, compared to 1.1 million tons in 2000 - 2001 (Boulos *et al.*, 2006). In Australia, it was estimated that 3.7 million tons of garden and food organics and wood residues were diverted and recycled from landfill in 2007 - 2008 (Biala, 2011).

Compost application is important for sandy soils which generally have low water and nutrient holding capacity and are less fertile than heavier textured soils. Crops growing in sandy soil strongly depend on fertiliser application and, in dry conditions, on frequent irrigation (Craul, 1986). Plant nutrients can be leached due to the high permeability (Shepherd and Bennett, 1998) and low water holding capacity of sandy soils (Zotarelli *et al.*, 2007). Leaching can reduce fertiliser use efficiency (Asseng *et al.*, 2001) and lead to ground and surface water contamination (Zotarelli *et al.*, 2007).

Clay addition to sandy soils can increase water and nutrient holding capacity for sandy soils (Harper and Gilkes, 1994; Reuter, 1994; Ismail and Ozawa, 2007) due to high binding capacity of clay and therefore could also reduce nutrient leaching from compost. However, there is little information about compost application and soil water content under drought condition, and/or about the effect of clay addition on nutrient leaching from compost.

Therefore, this thesis focused on two aspects of compost application: Soil water content and availability to plants, and nutrient leaching in sandy soils from compost.

This chapter is an overview of compost effects on soil properties and plant growth. This chapter also reviews the effect of clay on nutrient retention and potential environmental impacts for the soil-plant-water system.

1.2. Compost history and definition

Compost is a well-known term and has attracted scientific interest after Hutchinson and Richards (1921) demonstrated the conversion of straw to humus. Many experiments were carried out to test the Hutchinson and Richards process showing that straw can be decomposed over several months and has beneficial effects on field and garden crops (Collinson and Conn, 1929). Since the early 1940s compost has been used throughout the world for stabilization of organic residues such as municipal wastewater biosolids and yard trimmings, manures and brewery sludge (Rodale, 1943; Day and Shaw, 2001; Goldstein, 2001).

Compost is defined as stable aerobically decomposed organic matter (Paulin and O’Malley, 2008) and as the stabilized and sanitized product of composting (Insam and de Bertoldi, 2007). The product of the composting process which is a controlled decomposition process is resistant and includes complex organic materials (Thompson, 2007). This process is based on aerobic microbial breakdown which transforms organic materials into a variety of complex organic molecules (Paulin and O’Malley, 2008). Compost is usually dark brown and has an earthy appearance and smell (Thompson, 2007; Paulin and O’Malley, 2008).

1.3. Composting process

Composting differs from other decomposition systems because temperature and rate of decomposition are controlled (Misra *et al.*, 2003; Bernal *et al.*, 2009). Composting is referred to the biodegradation process of a mixture of organic substrate by bacteria, actinomycetes and fungi (Day and Shaw, 2001; Insam and de Bertoldi, 2007). These microbes attack, feed on and digest organic wastes, then these microbes are preyed upon by the second level of organisms, e.g. protozoa and beetles, mites. Finally, centipedes and ground beetles consume the second level organisms. The composting process has 3 stages; a rapid stage of decomposition, stabilization and humification (Insam and de Bertoldi, 2007), but Polprasert (1989) distinguishes 4 stages (Figure 1). In the first stage, mesophilic bacteria are predominant and the temperature in the compost pile increases to 35° C - 45° C. When the temperature exceeds 45° C, mesophilic bacteria are replaced by thermophilic bacteria (McKinley *et al.*, 1985). The increase in activity of the thermophilics leads to an increase in temperature up to 70° C. Eventually, when the substrate is depleted, the overall microbial activity deceases, the temperature falls (cooling stage) and the compost enters the maturation stage (McKinley *et al.*, 1985).

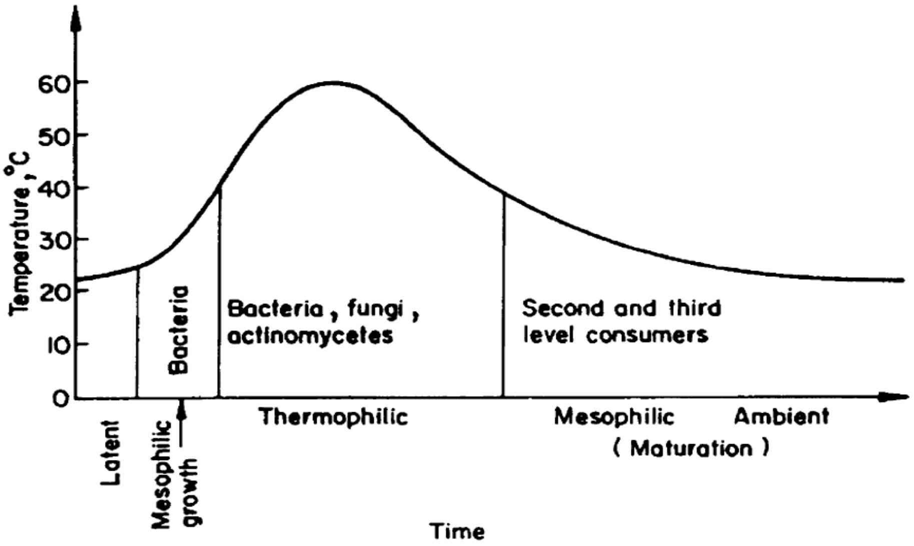

Figure 1. Composting process (From Polprasert, 1989).

1.4. Compost application forms

Compost application forms and timing in relation to crop establishment and placement influence effects of compost on soil properties and plant growth. Traditionally, compost is applied once or annually and by mulch or incorporation. Mulching is broadcast application of compost on the soil surface around plants whereas for incorporation the compost is incorporated into the topsoil or whole soil close to the plants (Figure 2).

Figure 2. Compost applied as mulch (left) and incorporation (right) in vineyard

Generally, both compost mulching and incorporation have positive effects on soil physical, chemical, biological properties of soils and plant growth (see 1.5 - 1.6). However, compost mulching and incorporation also have different effects. Compost mulching can reduce the incidence of diseases and pest and suppress weed (Pinamonti, 1998; Campbell and Sharma, 2007), but compost incorporation does not (Campell, 2003). Incidence of Botrytis or bunch rot of grapes was less on plots with mulched compost (composted mulches were produced from vineyard prunings, winery waste, garden organics, pine bark and animal manure) than un-mulched plots (Mundy and Agnew, 2002). Compared to unamended soils and compost incorporation, compost mulching improves water balance by evaporation reduction and reducing large fluctuations in soil temperature (Pinamonti, 1998; Naeini and Cook, 2000a; Taban and Naeini, 2006; Omran and Wanas, 2007). Incorporated compost increases hydraulic conductivity (Aggelides and Londra, 2000; Celik *et al.*, 2004) whereas mulched compost has no effect (Johnson *et al.*, 2006b). Compost incorporation has a greater effect on soil C, N content and bulk density than mulched compost which can be attributed to the addition of organic matter (Cogger *et al.*, 2008). Soil compaction and aggregation were more strongly reduced by incorporated than mulched compost. Compost incorporation results in higher levels of residual soil nitrate - N than mulched compost because of increased N mineralization when the compost mixed with soil. Mulched compost reduces soluble compounds leaching compared to compost incorporation due to the lower accessibility to soil organisms (Gonzalez and Cooperband, 2002).

Compost can be applied once or annually at the moderate application rates well adapted to sustainable agriculture, (Mamo *et al.*, 1999; 2000; Morlat, 2008). Compost applied once at high rate may cause plant water stress due to transient increase in salt concentration compared to repeated applications of smaller amounts (Mamo *et al.*, 2000; Morlat, 2008). Compost applied once at high rates also increase N loss (Mamo *et al.*, 2000) because the high N content which inhibits plant growth and production (Morlat, 2008). Annual addition of compost tended to result in consistent and adequate yields in the second and third year, but a single high rate application of compost may increase yield in the first year due to substantial modification of soil properties (Tester, 1990; Mamo *et al.*, 1999).

1.5. Effects of compost on soil properties

1.5.1. Physical properties

A primary benefit of compost application on soil physical properties is reduced bulk density and increased total porosity (Table 1). Based on the average of data shown in Table 1, compost application reduced bulk density by 17.5% and increased total porosity by 10.2%. The improved soil bulk density and total porosity is likely due to the low bulk density of compost (i.e. less than 1.3 g cm^{-1}) and high organic matter content. He *et al.* (1995) showed that the bulk density of seven municipal solid waste compost was from 0.22 to 0.74 g cm^{-3}. The compost effect usually increases with compost application rate (Jamroz and Drozd, 1999; Aggelides and Londra, 2000). Furthermore, compost application can improve soil structural stability (Tejada *et al.*, 2009), aggregate formation (Celik *et al.*, 2004; Sodhi *et al.*, 2009) and hydraulic conductivity (Curtis and Claassen, 2009). Compost can also increase soil water holding capacity (Aggelides and Londra, 2000; Curtis and Claassen, 2005).

Compost application can increase soil water content at field capacity and permanent wilting point, and plant available water (PAW) (Celik *et al.*, 2004; Curtis and Claassen, 2005; Taban and Naeini, 2006; Weber *et al.*, 2007; Mylavarapu and Zinati, 2009). Compost can retain greater amounts of water at field capacity and permanent wilting point than mineral soils with a greater difference at field capacity than at permanent wilting point (Hudson, 1994; Olness and Archer, 2005). On average compost increased the amount of PAW by 67.3% compared to the unamended control in the studies shown in Table 2. The effects of compost on PAW are related to the increase in micro- and macro-porosity (Table 1) because high porosity increases water retention capacity (Aggelides and Londra, 2000; Curtis and Claassen, 2005; Taban and Naeini, 2006). However, incorporation of yard waste compost did not increase plant available in fine-textured soils (Taban and Naeini, 2006; Curtis and Claassen, 2009). Additionally, the approach to measure PAW was *ex situ* using the pressure plate method (Klute, 1986). Using this method, the amount of PAW is the difference of soil water content at -0.01 MPa (i.e. field capacity) and -1.5 MPa (i.e. permanent wilting point) on repacked soil cores. However, the soil water content at field capacity of sieved samples was overestimated by an average of 30% above actual value (Elrick and Tanner, 1955) and soil water content at permanent wilting point was underestimated (Gee *et al.*, 2002). These previous studies suggest that compost can increase PAW, but little is known about compost effects on soil water content and availability of water to plants during drying and wetting cycles.

The effect of compost on soil physical properties is can be explained by the increase in organic matter content (Celik *et al.*, 2004; Korboulewsky *et al.*, 2004; Weber *et al.*, 2007; Hargreaves *et al.*, 2008; Lakhdar *et al.*, 2009). Organic matter concentration is positively correlated with hydraulic conductivity, water retention capacity and PAW (Celik *et al.*, 2004; Curtis and Claassen, 2005). Modelling showed that future organic matter content is higher in soils with compost and chemical fertilizers than with chemical fertilizers only or without fertilizers in Taiwan (Chen *et al.*, 1998).

Table 1. Effects of various composts on soil physical properties.

Compost type	Application form/rate	Soil type/condition	Crop	Effect	Reference
Poultry litter	Incorporation/ ≤ 50% (v/v)	Loamy sand/ Greenhouse	NA	Reduced bulk density Increased total porosity Increased soil water content	(Warren and Fonteno, 1993)
Municipal solid waste Sludge and poplar bark	Mulch/ 5 cm depth	Sandy loam/ field	Grapevine	Improved water permeability and storage Reduced evaporation	(Pinamonti, 1998)
Municipal solid waste	Incorporation/ 30, 60 and 120 t ha^{-1}	Loam/ field	Lettuce Cabbage	Reduced bulk density Increased total porosity Increased water retention at field capacity	(Jamroz and Drozd, 1999)
Sewage sludge and sawdust and town waste	Incorporation/ 39, 78 and 156 t ha^{-1}	Clay Loam/ field	Grass follow	Reduced bulk density Increased total porosity Increased hydraulic conductivity	(Aggelides and Londra, 2000)
Municipal solid waste	Mulch/ 34 t ha^{-1}	Loamy sand/ field	cotton	Reduced soil compaction Increased water infiltration	(Khalilian *et al.*, 2002)
Green waste compost	Incorporation/ 25 t ha^{-1}	Clayey loam/ field	Wheat Pepper Maize	Reduced bulk density Increased porosity Increased hydraulic conductivity Increased PAW Improved aggregation	(Celik *et al.*, 2004)

Table 1. Effects of various composts on soil physical properties (continued).

Compost type	Application form/rate	Soil type/condition	Crop	Effect	Reference
Yard waste compost from the municipal composting	Incorporation/ 274 t ha^{-1} 540 t ha^{-1}	Clayey soil/ field	NA	Increased PAW Increased water content at field capacity Decreased soil bulk density	(Curtis and Claassen, 2005)
Garden waste compost	Mulch and incorporation/ 50 t ha^{-1}	Loamy sand Loam/ glasshouse	Maize	Compost mulched increased soil water retention Reduced bulk density Compost mulched reduced evaporation	(Taban and Naeini, 2006)
Municipal solid waste	Incorporation/ ≤ 120 t ha^{-1}	Loamy sand/ field	Triticale (X *Triticosecale*)	Increased total porosity (1 month) Increased PAW	(Weber *et al.*, 2007)
Windrowed yard waste	Incorporation/ 540 t ha^{-1}	Loam Sand/field	Big squirrel tail plugs	Reduced bulk density Increased PAW Increased hydraulic conductivity	(Curtis and Claassen, 2009)
Organic dairy and cattle manure	Mulch/ ≤ 93 t ha^{-1}	Clay loam/ field	Blue grass	Increased infiltration rate Increased soil water content	(Johnson *et al.*, 2009)
Municipal solid waste and biosolid	Incorporation/ 19 t ha^{-1}	Loam/ field	Parsley	Increased soil water retention at PWP Reduced bulk density	(Mylavarapu and Zinati, 2009)
Vermicompost	Incorporation/ 2:7 (w/w)	NA/ greenhouse	Cabbage	Increased water holding capacity	(Wang *et al.*, 2010)

Table 2. Effect of compost on plant available water (PAW)

Compost type	Application form	Condition	Plant available water		Unit	Increased PAW (%)	Reference
			Unamended soil	Amended soil			
Green waste	Incorporation	Field	0.09	0.172	$m^3 m^{-3}$	92.2	(Celik *et al.*, 2004)
Yard waste	Incorporation	Field	4.0	9.3	%	132.5	(Curtis and Claassen, 2005)
Garden waste	Incorporation	Pot	7.1	8.6	%	21.2	(Taban and Naeini, 2006)
Municipal solid waste	Incorporation	Field	0.085	0.124	$m^3 m^{-3}$	45.9	(Weber *et al.*, 2007)
Municipal solid waste	Incorporation	Field	3.01	4.39	$m^3 m^{-3}$	45.8	(Mylavarapu and Zinati, 2009)

1.5.2. Chemical properties

Compost application changes soil chemical properties (Hargreaves *et al.*, 2008; Lakhdar *et al.*, 2009). The main benefits of compost on soil chemical properties are the increase in soil nutrients, efficiency of fertiliser nutrients and partial replacement of inorganic fertilisers.

Soil pH

The effect of compost on soil pH depends on the initial pH of soil and compost. Compost application can increase soil pH in acidic soils particularly at high application rate (Warren and Fonteno, 1993; Courtney and Mullen, 2008; Arthur *et al.*, 2011) because compost usually has neutral or slight alkaline pH and pH buffering capacity (Gallardo-Lara and Nogales, 1987). Carbon mineralization and the subsequent production of OH^- ions by ligand exchange as well as the addition of cations such as K^+, Ca^{2+} and Mg^{2+} with compost contribute to increased soil pH (Mkhabela and Warman, 2005). However, municipal solid waste (Pinamonti *et al.*, 1999) or dairy manure (Johnson *et al.*, 2006a) composts did not increase soil pH, and rice straw and sewage sludge compost decreased soil pH (Pinamonti *et al.*, 1999). Changes in pH can result in changes in the surface charge of soil particles which will in turn influence their nutrient binding capacity.

Soil electrical conductivity

Plants are negatively affected by excess salt (Na^+, K^+, Mg^{2+} and Cl^{-1}) in soil (salinity) and high Na concentrations on soil colloids (sodicity) can be detrimental to the soil structure. Compost application can increase soil electrical conductivity (EC) which is a measure of the salt concentration in the soil solution. This attributed to the high salt content of some composts (Arthur *et al.*, 2011) and is proportional to application rates (Castillejo and Castello, 2010). The EC of agricultural soils ranges from 0 to 4 dS m^{-1}, while EC of municipal solid waste compost ranges from 3.69 to 7.49 dS m^{-1} (Brady and Weil, 1996) and dairy manure compost has an EC of 32.8 dS m^{-1} (Johnson *et al.*, 2006a). The soil EC values can decline over time due to nutrient removal by crops and leaching (Zhang *et al.*, 2006; Herrera *et al.*, 2008). Compost EC is dependent on compost feedstock and procedure (Hicklenton *et al.*, 2001). In Australia, there are no EC limits for composts but the salt application rate is limited thus limiting compost application rate (Standard Australia, 2003).

Soil fertility

Compost application improves soil fertility by increasing the concentrations of N, P and other nutrients (Hargreaves *et al.*, 2008; Lakhdar *et al.*, 2009; Castillejo and Castello, 2010), but the effect varies with application rate and compost type. Compost is a valuable slow release nitrogen source with a stronger residual effect on soil fertility than most chemical fertilizers (Parr *et al.*, 1989) with effects persisting 5 years after application (Marchesini *et al.*, 1993). Less than 15% of N from municipal solid waste compost is released in the first year after application and 2-8% of the remaining compost-N in subsequent years (de Haan, 1981; Amlinger *et al.,* 2003). Nitrogen supply from compost through mineralization can be similar to inorganic soluble fertiliser (Mylavarapu and Zinati, 2009). However, N supply by compost also depends on the application rate. Aggelides and Londra (2000) found that compost did not improve total soil N concentrations at low rates (18 and 36 t ha^{-1}) in the first year of application and at the high rate (72 t ha^{-1}) only in the third year. The increase in N availability may also be transient because application municipal solid waste compost increased NO_3^- concentration for only 6 weeks after planting of cotton (Khalilian *et al.*, 2002).

Compost application can increase soil P supply (Jimenez *et al.*, 1993; Warren and Fonteno, 1993; Wang *et al.*, 2010). Compost can release inorganic P overtime through mineralization of organic P fractions in the compost. Up to 50% of total P in the compost is released in the first and second year after application (de Haan, 1981) which can increase plant P uptake (Mbarki *et al.*, 2008; Mylavarapu and Zinati, 2009).

Several studies have demonstrated that compost increased soil K concentrations (de

Haan, 1981; Aggelides and Londra, 2000; Mylavarapu and Zinati, 2009) and can also increase plant available K by providing cation exchange sites on the organic matter (Walker and Bernal, 2008; Mylavarapu and Zinati, 2009). Compost also increase the concentration of other nutrients such as Ca, Zn, Mn, and Cu in plants (Mylavarapu and Zinati, 2009).

1.5.3. Biological properties

Compost application increases the abundance of soil organisms such as microorganisms and nematodes (Khalilian *et al.*, 2002; Leroy *et al.*, 2007) and enzyme activity (Ferreras *et al.*, 2006; Cunha-Queda *et al.*, 2010). Compost addition enhances total microbial, fungal and bacterial biomass in soils (Pascual *et al.*, 1997; Lee *et al.*, 2004; Annabi *et al.*, 2007) which can be explained by a supply of labile organic C with compost (Annabi *et al.*, 2007) and the increased total soil organic carbon content (Pascual *et al.*, 1997; Korboulewsky *et al.*, 2002; Ferreras *et al.*, 2006). Soil basal respiration rate, a measure of microbial activity, is also increased by compost application compared to the unamended soils (Ferreras *et al.*, 2006) up to eight years after application (Pascual *et al.*, 1999).

1.6. Effect of compost on plant growth and development

1.6.1. Plant growth

The improvement of soil physical, chemical and biological properties by compost can improve plant growth. Compared to unamended soils, the application of compost can increase shoot and root growth of tomatoes (Levy and Taylor, 2003) and root depth of Serpentine perennial grass (*Elymus elymoides*) (Curtis and Claassen, 2005). Compost increased fresh weight of parsley (Mylavarapu and Zinati, 2009), barley yield (Lillywhite *et al.*, 2009) cotton seed weight (Khalilian *et al.*, 2002) and the marketable weight of Chinese cabbage (Wang *et al.*, 2010). Compost application also stimulates seed emergence (Taban and Naeini, 2006). The positive effects of compost on plant growth are due to a number of reasons including nutrient supply, improved soil structure (Wang *et al.*, 2010) and/or the increased soil water content.

1.6.2. Nutrient uptake

By supplying nutrients, particularly N, P and K, and organic matter, compost can improve plant nutrient uptake (Pinamonti, 1998; Evanylo *et al.*, 2008; Walker and Bernal, 2008; Mylavarapu and Zinati, 2009), but the effect depends on compost type as well as on application rate and method. Compost application increases plant growth and N mineralization rate, but high rates are required to meet the crop N needs (Evanylo *et al.*, 2008) to ensure a continuous N supply to plants from compost similar to the supply of N from inorganic fertilizer (Pinamonti, 1998; Mylavarapu and Zinati, 2009). Indeed, N recovery in sorghum biomass was significantly higher in the soil amended with compost in comparison to mineral-fertilized plots (Steiner *et al.*, 2008). Compost mulch increased the leaf concentration of K but decreased those of P, Ca and Mg (Pinamonti, 1998). The N, P and K uptakes of plants increase with increasing rate of compost (Tyler *et al.*, 1993).

1.6.3. Water uptake and gas exchange

Water is crucial to plant physiological processes and plants require a large quantity of water for growth and development with 50 - 90% of fresh weight of plant being water (Ehlers and Goss, 2003; Taiz and Zeiger, 2003; Lambers *et al.*, 2008). Water is a solvent for salts, and molecules and mediates of chemical reactions. Water is the medium of transport for carbohydrates, phytohormones and nutrients, and organic molecules to shoots, stems and leaves (Ehlers and Goss, 2003). If there is an insufficient water supply, herbaceous plants and plant organs that lack supporting sclerenchyma will lose strength and wilt (Ehlers and Goss, 2003). When plants lose turgor, certain physiological functions will not be carried out and photosynthesis is lower. Transpiration of water from leaves prevents overheating of the leaf surface which is critical in hot environments.

Compost application can increase transpiration and gas exchange of plant due to the increase in plant growth and leaf area index which increase potential water use by transpiration (Adamtey *et al.*, 2010). In turn, high water use for transpiration and photosynthesis stimulates dry matter production and leaf area index (Dagdelen *et al.*, 2006). Compost increases transpiration rate of Norway Maple (*Acer platanoides* L.) (Francesco and Baietto, 2007), tomatoes (Ozenc, 2008) and maize crops (Adamtey *et al.*, 2010), but compost application had no effect on net photosynthesis (Francesco and Baietto, 2007). On the other hand, Tyler *et al.* (1993) showed that compost increased both photosynthesis and stomatal conductance and this effect became stronger with increasing application rate.

The increase in transpiration especially towards the end of drying stage could also be due to enhanced water retention in soils as a result of reduced evaporation (Pinamonti, 1998; Naeini and Cook, 2000b; Johnson *et al.*, 2009) and higher soil organic matter. Transpiration is directly related to whether the stomata aperture and other factors such as available water content and aeration capacity of soils (Ozenc, 2008). Compost application stimulates root growth and volume (Ozenc, 2008; Johnson *et al.*, 2009), which can increase the ability of plants to uptake more water (Curtis and Claassen, 2005; Adamtey *et al.*, 2010). Mixing hazelnut husk compost with peat increased transpiration rate and root/shoot ratio (Ozenc, 2008). Indirectly, the enhanced root growth can influence plant growth through improved nutrient uptake and synthesis of plant growth regulators. Vermicompost can increase growth, biomass and yield of canola under moderate and severe drought stress (Rashtbari *et al.*, 2012). This could be due to higher soil water content, enhanced soil water holding capacity as well as greater root growth and thus uptake of water and nutrients.

1.7. Effect of clay on nutrient retention

As outlined above, compost can be applied to provide nutrients and water to plants, particularly in sandy soils. However, nutrients may be leached from the compost, thereby limiting its beneficial effect (Shepherd and Bennett, 1998; Mamo *et al.*, 1999; Basso and Ritchie, 2005). Further, effects of compost on soil water and nutrient retention may be transient due to mineralisation of compost over time. To induce more long-lasting soil improvement, farmers have applied clay to sandy soils and more recently, compost has been amended with clay to increase its longevity.

Addition of clay to sandy top soil (claying) has decreases water repellence and improves crop yield (McKissock *et al.*, 2002; Al-Omran *et al.*, 2005; Ismail and Ozawa, 2007) by limiting percolation losses and increasing water retention while maintaining adequate infiltration rate (Al-Darby, 1996; Emerman, 1996). The increased water retention is a result of improved soil aggregation. Aggregate stability increases with clay content because the clay particles bind soil particles together (Kemper and Koch, 1966).

Compost provides organic matter and nutrients (Celik *et al.*, 2004; Korboulewsky *et al.*, 2004; Weber *et al.*, 2007; Hargreaves *et al.*, 2008; Lakhdar *et al.*, 2009). However, the application of compost can increase nutrient leaching, including NO_3^-N (Mamo *et al.*, 1999) and dissolved organic matter (DOM) (Borken *et al.*, 2004; Wright *et al.*, 2010). Dissolved organic matter from compost can also modify the amount of composition of native dissolved organic carbon (DOC) (Chantigny, 2003) and increase Cu, Zn, and Cd concentrations (Beesley and Dickinson, 2010). Clay minerals are very important in stabilisation of soil organic matter (Hassink, 1991). Clay influences the rate of mineralisation of organic matter added to soil (Amato and Ladd, 1992; Nelson *et al.*, 1997) because clay reduces accessibility of organic matter to soil microbes by sorption of organic matter to clay and occlusion in aggregates (Nelson *et al.*, 1997). Therefore, one option to increase the sorption capacity and thereby nutrient holding capacity and effectiveness of compost could be an addition of clay to soil or compost.

1.8. Conclusion and research gaps

Compost application increases soil water and nutrient holding capacity. Compost application can increase available nutrients directly from compost, but also indirectly by increasing nutrient sorption capacity.

Nutrients added with the compost may be lost via leaching (Shepherd and Bennett, 1998; Mamo *et al.*, 1999; Basso and Ritchie, 2005), particularly in sandy soils which have a low nutrient retention capacity. The following research gaps remain to be addressed:

1. Can compost increase soil water content and improve plant growth under drought stress?
2. How long does compost have positive effects on plant growth after a single application?
3. What effect do mulched and incorporated compost have on soil water content and plant growth?
4. What effect does clay addition to compost or soil have on nutrient leaching?

Therefore, the present study has the following aims:

1. Assess effects of compost on soil water content and plant physiology under drought stress (Chapter 2).
2. Determine whether a single application of compost three years previously has effect on soil and plant growth under drought stress (Chapter 3).
3. Investigate effects of compost application methods (incorporation or mulching) on plant growth and yield in the field (Chapter 4).
4. Investigate if clay addition to compost can reduce nutrient leaching from compost in sandy soil (Chapter 5).
5. Assess effects of clay addition to a sandy soil on C loss from compost extract (Chapter 6).

The pot experiments were to study compost effects under controlled drought conditions which could lead to practical recommendations for compost application to agriculture. The field experiment was to study the longer term effects of compost on water content at different soil depths and plant growth in an irrigated horticultural system. The incubation experiments were included to determine the potential of clay addition to compost or soil under defined conditions which could be the basis of future field trials.

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CHAPTER 2

EFFECTS OF COMPOST ON WATER AVAILABILITY AND GAS EXCHANGE IN TOMATO DURING DROUGHT AND RECOVERY

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Nguyen, T.T., Fuentes, S., Marschner, P. (2012) Effects of compost on water availability and gas exchange in tomato during drought and recovery. *Plant, Soil and Environment*, **58**. 495-502.

STATEMENT OF AUTHORSHIP

Effects of compost on water availability and gas exchange in tomato during drought and recovery

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Performed experiment, analyses of soil, compost and plant samples, data analysis and interpretation, wrote manuscript, acted as a corresponding author.

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Contributed to planning of experiments, discussions, proof-reading of manuscripts, supervised development of work.

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Petra Marschner

Supervised development of work, data interpretation and manuscript evaluation and correction

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CHAPTER 3

GROWTH AND WATER USE EFFICIENCY OF *CAPSICUM ANNUUM* IN A SILT LOAM SOIL TREATED THREE YEARS PREVIOUSLY WITH A SINGLE COMPOST APPLICATION AND REPEATEDLY DRIED

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Growth and water use efficiency of *Capsicum annuum* in a silt loam soil treated three years previously with a single compost application and repeatedly dried

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Growth and water use efficiency of *Capsicum annuum* in a silt loam soil treated three years previously with a single compost application and repeatedly dried

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Abstract

Mulched compost can reduce irrigation requirements by decreasing soil evaporation. However, it is not known how long this effect lasts after a single compost application. Pepper (*Capsicum annuum* L.), cv. Giant Bell, plants were grown in a silt loam (Calcarosol) which had received mulched compost once three years previously, and in a corresponding unamended control. After 41 days of sufficient water supply, plants were divided into two water regimes: (i) sufficient water supply until the end of the experiment (67 days) and (ii) two transient drought cycles, separated by one week of sufficient water supply. Compost applied once three years previously increased soil organic C and total N, and dry root mass and root length under well watered and drought stressed conditions. The single compost application increased total available water, total water used, and water availability to plants when well watered, but did not affect gas exchange and had no effect on water use efficiency and recovery capacity of plants after drought stress. Even three years after application, mulched compost increases the ability of plants to take up water by stimulating root growth.

Keywords: *Capsicum annuum*, drought, gas exchange, organic amendment, water consumption

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Addition of compost improves biological and physical properties of soils, including increased microbial biomass, micronutrient levels and water availability to plants (Aggelides and Londra, 2000). Addition of compost also increases growth and yield of vegetables and is used for production of pepper (*Capsicum annuum* L.) (Ghoname and Shafeek, 2005). Composts are often only applied, as mulch, every few years and it is unclear how long compost affects water, nutrient availability, and plant response to drought after a single application. The study was undertaken to investigate the effect of mulched compost applied once three years previously on water availability to plants and water use efficiency of *C. annuum* grown under well watered and transient drought stress conditions. Pepper was selected because of its sensitivity to water stress (Costa and Gianquinto, 2002) and importance as a vegetable crop.

Materials and Methods

Pepper, cv. Giant Bell seeds were germinated in 100-cell tray on coco peat propagation medium in a glasshouse under natural light (average 23°C and 54% RH) with 12-h photoperiod. The seedlings was irrigated to field capacity every second day. One m^3 of bulk propagation coco peat medium was fertilised with 1.8 kg of mini Osmocate® (16N:3P:9K). Seedlings of 42 days old, approximately 5 cm tall, were transplanted into pots containing a Calcarosol (Isbell, 2002) (41.2% sand, 55.1% silt and 3.7% clay) which received a single application of 150 $m^3 \cdot ha^{-1}$ of compost derived from wood chips, bark, and leaves from trees (composted in windrows as mulch three years previously (Compost) or which did not receive compost (Control). The few compost particles visible on the soil surface were removed before collection of the soil. To ensure similar N and P supply, soil N and P concentrations were adjusted to 100 $mg \cdot kg^{-1}$ and 200 $mg \cdot kg^{-1}$ soil with $(NH_4)_2SO_4$ and KH_2PO_4, respectively. Three-kg of soil was placed in 2.9 L pots which were lined with a plastic bag to prevent water loss.

Plants were maintained at an average 23^{o}C and 54% relative humidity in a glasshouse from July to November 2011 (corresponding to winter-spring in the Southern hemisphere). Plants were watered to 70% maximum water holding capacity (MWHC) every third day until 40 days after planting (DAP). Then plants were divided into two water treatments. Four plants of each compost treatment were watered daily to 70% MWHC from 41 DAP until harvest (67 DAP). The other 4 plants per treatment were subjected to two drought stress cycles separated by one week of sufficient water supply. For the first cycle, watering was withheld from 41 DAP until all plants wilted and stomatal conductance was close to zero (45 DAP). Plants were rewatered to 70% MWHC and maintained at this water content for 1 week. For the second drought cycle (52 DAP), water was again withheld until plants wilted and stomatal conductance was close to zero (60 DAP) after which plants were rewatered to 70% MWHC and maintained at this water content until the end of the experiment (67 DAP). To determine soil water content at field capacity (FC), permanent wilting point (PWP) and total available water (TAW), another four plants from each treatment were watered to 100% MWHC on 41 DAP, after which water was withheld until all leaves and shoot tips were visually wilted (PWP).

Soil water content was measured with a time domain reflectometrer probe (Hydrosense, Campbell Scientific, Logan, UT) 15 hrs after watering to 100% MWHC and at PWP (visually wilted). Total available water is the soil water content at 100% MWHC (field capacity) minus that at PWP (TAW=FC-PWP). Soil water content was recorded daily during drought stress periods in well watered and drought stressed plants, and calculated after determining the calibration curve of a time domain reflectometrer probe for the soils (Bourgeau-Chavez et al., 2010). Water availability to plants was calculated as soil water content at a given day minus soil water content at PWP.

Photosynthetic rate (A), transpiration rate (E) and stomatal conductance (g_s) were determined between 11:00 and 14:00 on the third mature leaf from the top using a gas exchange system (LCA4, ADC BioScientific Ltd, Hoddesdon, UK) on the last day of drought stress periods and the first day after re-watering. Stem water potential (Ψ_s; MPa) was measured with a pressure chamber (1005 Pressure Chamber Instrument, PMS Instrument Company, Albany, NY) at the same time as the gas exchange measurements (Scholander et al., 1965). Pot weight was recorded prior to each watering to assess amount of water used. Water use efficiency (WUE) was calculated as total shoot and root dry mass divided by total water used.

Shoot length and number, and leaf number were recorded weekly throughout the experiment. Shoot and root dry weight at the end of experiment was determined after drying in a forced air oven at 65°C to constant weight. Soil particles were removed from roots by washing and total root length determined using an image analysis system (WinRHIZO, Regent Instruments Inc., Quebec, Canada).

Pots were arranged in a split-plot design with water treatment as the main effect and soil treatment (compost and control) as the split with 4 replicates. General properties of the soil were analysed by one-way ANOVA. The other data were analysed by two-way ANOVA. If interactions were significant they were used to explain results. If main effects were used to explain results differences between means were compared using least significant different (LSD, $P \leq 0.05$) and least squares means analysis, Tukey's test in GenStat for Windows® (11th ed. 2005, Hempstead, UK).

Results and Discussion

Mulched compost application affects soil properties due to nutrients provided from the compost (Pinamonti, 1998). Compared to the unamended control, mulched compost application three years previously increased soil organic carbon and total N concentration, and reduced pH, EC and soil total P (Table 1). Compost application had no effect on bulk density or porosity (data not shown). Weber et al. (2007) found that municipal solid waste compost only improved porosity within 5 months after application.

Shoot length, shoot number and number of leaves did not differ between compost treatments throughout the experiment (data not shown). Compost applied three years previously did not affect dry shoot mass, but increased dry root mass, total root length and decreased shoot to root ratio (Table 2,3). Drought stress reduced dry shoot weight and total water used (Table 2,4) irrespective of compost treatment (Table 2). Mulched compost can increase plant nutrient status (Pinamonti, 1998; Weber et al., 2007), but plant nutrient concentrations did not differ between compost treatments in this study (data not shown). However, mulched compost increased the ability of the plants to extract water, which can be explained by stimulation of root dry mass and root length in well watered and drought stressed plants (Table 2,3). Mulched compost applied three years previously increased total water used (Table 2,3). Similarly, Curtis and Claassen (2005) showed that municipal yard waste compost increased the ability of *Elymus elymoides* (Raf) Swezey to extract water due to greater root proliferation. In the present study, mulched compost increased the total available water (Table 5) which stimulated root growth (Table 3). However, WUE did not differ between well-watered and drought stressed plants or soil treatments (Table 2). Mulched compost can reduce water loss by reducing direct soil evaporation (Pinamonti, 1998), but this does not apply in the current study because mulch particles in the compost treatment was removed before collecting the soil for the experiment. Photosynthesis and transpiration rates, as well as stomatal conductance, were higher during the first than the second drought cycle (Table 6,7). In all treatments, and both drought cycles, photosynthesis, transpiration rates and stomatal conductance were lower in drought stressed plants before rewatering than in well-watered plants. Transpiration rate and stomatal conductance of plants before rewatering in drought stress cycle 2 were higher in soil which received mulched compost three years previously, compared to those of the control without compost amendment: 0.94 and 0.69 mmol $H_2O \cdot m^{-2} \cdot s^{-1}$, and 0.04 and 0.03 mmol$\cdot m^{-2} \cdot s^{-1}$, respectively. In drought stress cycle 1, transpiration rate and stomatal conductance recovered quickly after rewatering of drought-stressed plants to levels of the well-watered plants, but photosynthesis rate did not recover to that of the well watered plants (Table 6,7). Drought stress reduced stem water potential in both compost treatments compared to well-watered plants with a greater decrease in the second drought cycle (data not shown). Stem water potential increased to levels similar to the well-watered plants after rewatering irrespective of compost treatment (data not shown). The interaction between mulched compost and water treatment was significant only for transpiration rate and stomatal conductance before rewatering in drought stress cycle 2 (Table 6,8). Mulching with compost three years previously did not affect the ability of plants to recover after a period of drought stress (Table 6) probably because compost did not increase water availability to plants under drought stress compared to unamended control (Fig. 1).

The single compost mulch application three years previously affected soil properties but did not increase dry shoot mass and water use efficiency in well watered and drought stressed plants. However, mulched compost stimulated root growth and the ability of plants to extract water, and increased water availability to plants under well watered conditions. Further research should investigate nutrient availability and plant growth at different times after compost application to better understand temporal changes in these properties after a single compost application.

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Table 1. Properties of Calcarosol soil receiving mulched wood and leaf compost at 150 $m^3 \cdot ha^{-1}$ once three years previously (Compost) and control without added compost (Control).

Treatment[a]	pH	EC[b] (mS·cm^{-1})	MWHC (%)	TOC (g·kg^{-1})	Total N (g·kg^{-1})	Total P (g·kg^{-1})	Available N (mg·kg^{-1})	Available P (mg·kg^{-1})
Compost	6.84a[c]	1.57a	444a	11.2b	15.8b	0.6a	29a	24.4a
Control	7.32b	1.92b	402a	8.0a	13.2a	0.8b	25a	25.0a

[a] n = 3 and 4 for physical and chemical properties, respectively.

[b] EC is electrical conductivity, MWHC is maximum water holding capacity, and TOC is total organic carbon.

[c] within column means followed by the same letter are not significantly different at $P \leq 0.05$, Tukey's test.

Table 2. ANOVA of mulched wood and leaf compost and water treatment on bell pepper shoot and root dry mass, root length, shoot to root ratio, total water used and water use efficiency (WUE) at fruit setting.

	Mean square					
Source	Dry shoot mass (g/plant)	Dry root mass (g/plant)	Root length (m/plant)	Shoot to root ratio	Total water used (kg/plant)	WUE ($g\cdot kg^{-1}$)
Mulched compost (M)	0.9 ns	4.0**	13788*	7.79*	0.99***	0.002 ns
Water treatment (W)	3.3*	0.6 ns	5124 ns	0.69 ns	0.66***	0.004 ns
M × W	1.6 ns	0.01 ns	24 ns	0.01 ns	0.15 ns	0.003 ns
Error	0.8	0.6	40	0.98	0.19	0.16
Coefficient variation (%)	5.3	19.9	21	19.0	2.8	5.9

ns,*,**,*** non-significant or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively, ANOVA.

Least square means are identical to the means shown in figures and tables.

Table 3. Effect of mulched compost on dry root mass, root length, shoot to root ratio and total water used of bell pepper plants at fruit setting. Plants were grown in a Calcarosol with, or without, wood and leaf compost at 150 $m^3 \cdot ha^{-1}$ three years previously.

Treatment	Dry root mass (g/plant)	Root length (m/plant)	Shoot to root ratio	Total water used (kg/plant)
Compost	3.56b[a]	222.60b	4.44a	7.07b
Control	2.56a	163.89a	5.84b	6.08a

[a] values in columns followed by the same letter are not significantly different at $P \leq 0.05$, Tukey's test.

Table 4. Effect of drought stress on dry root mass and total water used of bell pepper plants at fruit setting. Plants were grown in a Calcarosol with or without wood and leaf compost at 150 $m^3 \cdot ha^{-1}$ three years previously.

Treatment	Dry root mass (g/plant)	Total water used (kg/plant)
Well watered plants	3.25b[a]	7.03b
Drought stressed plants	2.86a	6.62a

[a] values in columns followed by the same letter are not significantly different at $P \leq 0.05$, Tukey's test.

Table 5. Soil water content at field capacity (FC) and permanent wilting point (PWP) of pepper plants at flowering and total available water (TAW) of soil that received wood and leaf compost at 150 $m^3 \cdot ha^{-1}$ three years previously (Compost) and unmulched control (Control).

	Water content ($g \cdot kg^{-1}$)		
Treatment	FC	PWP	TAW ($g \cdot kg^{-1}$)
Compost	496.9b[a]	59.9b	437.0b
Control	419.2a	42.6a	376.6a

[a] values in columns followed by the same letter are not significantly different at $P \leq 0.05$, Tukey's test.

Table 6. ANOVA of mulched compost and water treatments on photosynthesis, transpiration, and leaf stomatal conductance of bell pepper plants at fruit setting before (BW) and after rewatering (AW) in stress cycle 1 and 2. Plants were grown in a Calcarosol with, or without, wood and leaf compost at 150 $m^3 \cdot ha^{-1}$ three years previously before (BW) and after rewatering (AW) in stress cycles 1 and 2.

	Mean square											
	Photosynthesis rate ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$)				Transpiration rate ($mmol\ H_2O \cdot m^{-2} \cdot s^{-1}$)				Leaf stomatal conductance ($mmol \cdot m^{-2} \cdot s^{-1}$)			
	Stress cycle 1		Stress cycle 2		Stress cycle 1		Stress cycle 2		Stress cycle 1		Stress cycle 2	
Source	BW	AW	BW	AW	BW	AW	BW	AW	BW	AW	BW	AW
Mulched compost (M)	0.13 ns	6.0 ns	0.01 ns	0.01 ns	1.71 ns	1.02 ns	0.25**	0.27 ns	0.19 ns	0.016 ns	0.001***	0.001 ns
Water treatment (W)	192.79***	21.7 *	48.62***	4.32 ns	37.06***	1.76 ns	5.96***	1.45*	0.54*	0.021 ns	0.012***	0.005*
M × W	7.5 ns	10.2 ns	0.08 ns	0.08 ns	3.25 ns	0.34 ns	0.20**	0.35 ns	0.21 ns	0.009 ns	0.001***	0.001 ns
Error	2.06	1.9	0.37	1.18	0.96	0.61	0.15	0.47	0.3	0.074	0.007	0.029
Coefficient of variation (%)	42.1	24.7	16.1	26.6	43.7	30.2	18.0	34.6	147.2	51.6	20.3	47.4

ns,*,**,*** non-significant or significant at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively, ANOVA.

Table 7. Effect of drought on photosynthesis, transpiration, and leaf stomatal conductance of bell pepper plants at fruit setting before (BW) and after rewatering (AW) in stress cycles 1 and 2. Plants were grown in a Calcarosol with, or without, wood and leaf compost at 150 $m^3 \cdot ha^{-1}$ three years previously.

	Photosynthesis rate ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$)			Transpiration rate ($mmol\ H_2O \cdot m^{-2} \cdot s^{-1}$)			Leaf stomatal conductance ($mmol \cdot m^{-2} \cdot s^{-1}$)		
	Stress cycle 1		Stress cycle 2	Stress cycle 1	Stress cycle 2		Stress cycle 1	Stress cycle 2	
Treatment	BW	AW	BW	BW	BW	AW	BW	BW	AW
Well watered plants	8.36b[a]	8.87b	4.02b	3.71b	1.43b	1.67b	0.39b	0.06b	0.08b
Drought stressed plants	1.41a	6.24a	0.53a	0.67a	0.2a	1.06a	0.02a	0.01a	0.04a

[a] values in columns followed by the same letter are not significantly different at *P*≤0.05, Tukey’s test.

Table 8. Interaction effect of mulched compost and water treatment on transpiration rate and stomatal conductance of bell pepper plants at fruit setting before (BW) in stress cycle 2. Plants were grown in a Calcarosol with, or without, wood and leaf compost at 150 $m^3 \cdot ha^{-1}$ three years previously.

Water × Mulched compost	Transpiration rate ($mmol\ H_2O \cdot m^{-2} \cdot s^{-1}$)	Leaf stomatal conductance ($mmol \cdot m^{-2} \cdot s^{-1}$)
Well watered plants		
Compost	1.67c[a]	0.08c
Control	1.19b	0.05b
Drought stressed plants		
Compost	0.22a	0.01a
Control	0.19a	0.01a

[a] Values in columns followed by the same letter are not significantly different at $P \leq 0.05$, Tukey's test.

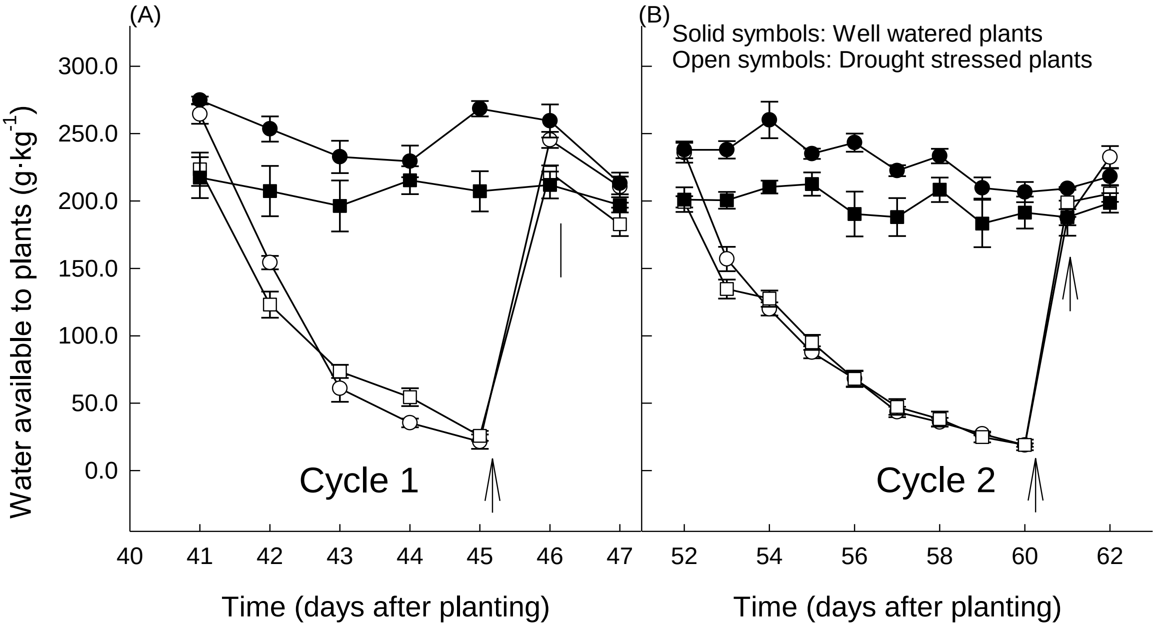

Figure 1. Water available to plants in the first (A) and second (B) drought stress cycle in well watered (solid symbols) and drought stressed (open symbols) conditions during drought stress and recovery periods in the silt loam soil which received compost once three years previously (●, ○) and unamended control (without wood and leaf compost three years previously) (■, □) treatments. Left arrow indicates the 1st day before rewatering and the right arrow indicates the 1st day of after rewatering. n = 4, bars are means ± standard error. Bell pepper plants were grown in 2.9 L pot (17 cm top dia and 17 cm high) with Calcarosol amended with wood and leaf compost at 150 $m^3 \cdot ha^{-1}$ three years previously, or was unamended.

CHAPTER 4

EFFECT OF INCORPORATED OR MULCHED COMPOST ON LEAF NUTRIENT CONCENTRATIONS AND PERFORMANCE OF *VITIS VINIFERA* CV. MERLOT

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Effect of incorporated or mulched compost on leaf nutrient concentrations and performance of *Vitis vinifera* cv. Merlot

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CHAPTER 5

ADDITION OF A FINE-TEXTURED SOIL TO COMPOST TO REDUCE NUTRIENT LEACHING IN A SANDY SOIL

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Addition of a fine-textured soil to compost to reduce nutrient leaching in a sandy soil

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Abstract. Compost addition to soil can increase nutrient availability, but if added to sandy soils, nutrients can be rapidly leached. Clay added to compost could increase nutrient retention and reduce nutrient leaching due to binding to the clay. An incubation experiment was conducted to assess the effect of addition of a fine-textured soil (34% clay) to garden waste compost on nutrient availability and leaching in a sandy soil. The sandy soil was non-amended or amended with compost only, at a rate 27.3 g kg^{-1}, or with a mixture of compost and 5% or 20% (w/w) of fine-textured soil. Two additional treatments included sandy soil amended with only the fine-textured soil at rates similar to those added with compost. Soil, compost, and fine-textured soil were mixed and packed to a bulk density of 1.22 g cm^{-3}. Soil respiration was measured over 23 days. On days 1, 5, and 23, the soils were leached with 50 mL reverse-osmosis water, and the following parameters were measured in the leachate: water-soluble organic carbon (OC), inorganic nitrogen (N), and phosphorus (P); water-soluble OC and available N and P were measured in the soil after leaching. Compost increased nutrient availability and leaching compared with the non-amended control. Addition of the fine-textured soil to compost reduced cumulative respiration and N and P leaching, with the effect more pronounced at 20% (w/w). Addition of the fine-textured soil alone had no effect on nutrient availability and leaching because of the low nutrient concentration in this soil. This study showed that addition of fine-textured soil to compost can reduce N and P leaching, which could enhance and prolong the positive effects of compost on soil fertility.

Additional keywords: clay, compost, N and P availability, N and P leaching, water-soluble carbon.

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Introduction

Sandy soils generally have low water- and nutrient-holding capacity and are less fertile than fine-textured soils. Therefore, crops growing in sandy soil strongly depend on fertiliser application and, in dry conditions, on frequent irrigation (Craul 1986). Although plant growth and yield can be increased by frequent fertilisation and irrigation, this can also cause environmental problems. Nutrients can be leached due to the high permeability (Shepherd and Bennett 1998) and low water-holding capacity of sandy soils (Zotarelli *et al*. 2007). Leaching can reduce fertiliser-use efficiency (Asseng *et al.* 2001) and lead to surface- and ground-water contamination (Zotarelli *et al*. 2007).

Composts are used widely in agriculture and horticulture, especially in sandy soils. Compost addition increases total porosity (Jamroz and Drozd 1999; Aggelides and Londra 2000) and water-holding capacity (Curtis and Claassen 2005) and improves structural stability (Tejada *et al*. 2009) due to the addition of organic matter. Compost also increases the amount of available nutrients (Warren and Fonteno 1993; Johnson *et al.* 2006; Weber *et al*. 2007) directly by nutrients contained in the compost, and indirectly by increasing nutrient-sorption capacity (Weber *et al*. 2007). However, nutrients added with the compost may be lost via leaching (Shepherd and Bennett 1998; Mamo *et al*. 1999; Basso and Ritchie 2005), particularly in sandy soils which have a low nutrient-retention capacity. Amending sandy soils with clay can increase water- and nutrient-holding capacity and productivity (Harper and Gilkes 1994; Reuter 1994; Ismail and Ozawa 2007). Thus, one option to increase the sorption capacity and thereby nutrient-holding capacity and effectiveness of compost could be addition of clay, but this has not yet been investigated. A local compost producer is currently testing this option by adding a fine-textured soil (34% clay) to compost before applying it in the field (P. Wadewitz, pers. comm.).

The aim of this study was to investigate the effect of addition of this fine-textured soil to garden waste compost on nutrient availability and leaching in a sandy soil. We hypothesised that, compared with compost alone, addition of the fine-textured soil to compost will increase nutrient-holding capacity of sandy soil and reduce nutrient leaching from compost.

Materials and methods

Soil and compost

Sandy soil (0–15 cm; 89% sand, 3% silt, and 8% clay) was collected from Monarto, South Australia (35°6′S, 139°37′E). The region is semi-arid and has a dry Mediterranean climate. The sandy soil was air-dried at room temperature and all plant debris was removed manually before sieving to <2 mm (Table 1). The fine-textured soil, a sandy clay loam (0–15 cm: 51% sand, 15% silt, and 34% clay) was collected in Brinkley, South Australia (35°2′S, 139°2′E) (Table 1). Qualitative X-ray diffraction (XRD) analysis showed that the main clay mineral in this soil is illite (15–20% by weight), followed by kaolinite (7–12%) and smectite (5–10%). This soil was chosen because it has been added to compost to enhance the effects of compost by a local compost producer who supplied the fine-grade garden compost (Table 1).

Treatments

The sandy soil was adjusted to 80% of water-holding capacity (WHC, 49.8 g kg soil^{-1}) with reverse-osmosis water; this water content was chosen because it had been shown to result in maximal soil respiration in soils of similar texture (Setia *et al.* 2011). The wetted soil was pre-incubated for 14 days at 25°C to reactivate the soil microbes. A pre-incubation for 14 days was used on the basis of Butterly *et al.* (2009), who showed that microbial activity was stable from 10 days after rewetting air-dry soils.

The pre-incubated soil was left unamended (control) or amended with only fresh compost (water content at 32%) at a rate 27.3 g kg^{-1} (i.e. equivalent to 50 t ha^{-1}) or with the same total weight added as compost mixed with the fine-textured soil at 5% and 20% (w/w) (i.e. corresponding to rates of compost of 26.0 and 21.9 g kg^{-1}, and fine-textured soil of 1.3 and 5.4 g kg^{-1}, respectively), or with only the fine-textured soil at rates similar to those added with compost. The treatments with the fine-textured soil received additional water to achieve 80% WHC. Thus, the treatments were: control (non-amended sandy soil), CT (sandy soil + compost only), CT5 (sandy soil + a mixture of compost and 5% the fine-textured soil), CT20 (sandy soil + a mixture of compost and 20% the fine-textured soil), CY5 (sandy soil + 5% fine-textured soil alone), CY20 (sandy soil + 20% fine-textured soil alone). Destructive sampling was carried out on days 1, 5, and 23 with four replications per treatment and sampling day.

Table 1. Physical and chemical properties of sandy soil, fine-textured soil, and compost

For physical properties *n* = 3, for chemical properties *n* = 4. n.a., Not applicable

Properties	Unit	Sandy soil	Fine-textured soil	Compost
$pH_{1:5}$		8.8	8.7	8.2
$EC_{1:5}$	mS cm^{-1}	0.1	0.3	3.5
Bulk density	g cm^{-3}	1.2	1.3	n.a.
Water-holding capacity	g kg^{-1}	62	237	n.a.
Cation exchange capacity	cmol(+) kg^{-1}	13.8	23.2	21.7
Surface area	m^2 g^{-1}	0.5	70.9	n.a.
Total organic carbon	g kg^{-1}	2.0	2.4	126.5
Water-soluble carbon	g kg^{-1}	1.8	3.3	76.1
Total nitrogen	g kg^{-1}	0.4	0.4	11.7
Total phosphorus	g kg^{-1}	0.1	0.2	1.6
Available nitrogen	mg kg^{-1}	11.2	100.1	802.6
Available phosphorus	mg kg^{-1}	0.8	21.5	13.6
C/N ratio		5.0	6.0	10.8

Pre-incubated sandy soil without or with compost and/or the fine-textured soil (50 g) was filled into polyvinyl cores (3.7 cm width, 5.0 cm height) with a nylon mesh base (0.75 µm; Australian Filter Specialist Pty Ltd, Huntingwood, NSW) and packed to a bulk density of 1.22 g cm^{-3}. The cores were placed into 1-L glass jars, after which the jars were sealed with gas-tight lids equipped with septa to allow quantification of the CO_2 concentration in the headspace. The jars were incubated in the dark at 22–25°C for 23 days.

At sampling, the cores were placed vertically in plastic funnels with the mesh facing down. Each core was leached five times with 10 mL of reverse-osmosis water (i.e. 50 mL). The leachate was centrifuged at 10 000 rpm for 15 min and analysed for water-soluble organic carbon (OC), inorganic nitrogen (N), and phosphorus (P). The water-soluble OC and available N and P were also measured in the soil after leaching. All treatments were adjusted to 80% WHC before leaching, and therefore, the volume of the leachate was similar in all treatments (i.e. 35.2 mL).

Nutrient leaching (C, N, and P; %) from the compost $\mathrm{Nut_{leach}}$ was calculated as:

$$\mathrm{Nut_{leach}}\,(\%) = [(\mathrm{Nut_{leachCT}} - \mathrm{Nut_{leachS}})/\mathrm{Nut_{total}}] \times 100 \quad (1)$$

where $\mathrm{Nut_{leachCT}}$ (mg kg^{-1}) is the C or N or P leaching from compost treatments, $\mathrm{Nut_{leachS}}$ (mg kg^{-1}) is the C or N or P leaching from the non-amended sandy soil, and $\mathrm{N_{total}}$ (mg kg^{-1}) is the initial total nutrient concentration from the added compost.

Analyses

Respiration (CO_2 release) was measured by quantifying the headspace CO_2 concentration within each jar with a Servomex 1450 infrared gas analyser (Servomex, Crowborough, UK). Due to the decline in respiration rates over time, the CO_2 concentration was measured daily for the first 5 days and then every second day until the end of the experiment (23 days). For each measurement period, an initial measurement was taken immediately after closing the jars after refreshing the air in the jars (T_0, CO_2 concentration at time 0). After the second measurement (T_1, CO_2 concentration at time 1), the jars were opened and the headspace in the jars was refreshed by a fan. The relationship between CO_2 concentration and detector response was determined by linear regression, by injecting known amounts of CO_2 into jars similar to those used for the samples, and was then used to calculate the CO_2 concentration in the jars with soils. The CO_2 evolved from each sample was calculated as the difference between T_1 and T_0 for each measurement period. The calculated CO_2 concentration was multiplied by the gas volume of the jars to obtain the mL CO_2-C respired during each measurement period.

Soil texture was determined by the hydrometer method as described by Gee and Or (2002) and textural classification was based on the Australian Soil Classification (Isbell 2002). The pH and electrical conductivity (EC) were determined in a 1 : 5 soil : water extract after 1 h end-over-end shaking at 25°C (Rayment and Higginson 1992). The water-holding capacity was determined by using a sintered glass funnel connected to a 100-cm water column (matric potential –10 kPa) (Wilke 2005). The specific surface area was determined by the water vapour sorption method (Newman 1983) using $LiNO_3$, $KC_2H_3O_2$, and LiCl to obtain different water vapour pressures. The mineralogy of the <2 µm clay fraction of the fine-textured soil was determined by XRD (Brindley 1980). The cation exchange capacity was determined by saturation with Na (Rhoades 1982).

Total OC was determined by wet oxidation and titration (Walkley and Black 1934). The water-soluble OC concentration was determined by oxidation with $K_2Cr_2O_7$ and H_2SO_4, followed by titration with acidified $(NH_4)_2Fe(SO_4)_2{\cdot}6H_2O$ (Anderson and Ingram 1993), and sucrose was used as a standard.

To determine total P, the soil samples were digested in HNO_3 and $HClO_4$ (6 : 1), and for total N, samples were digested in H_2SO_4 and H_2O_2 (2 : 1). Total P in the digest was measured by the phosphovanado-molybdate method according to Hanson (1950). Total N was measured by the distillation method (McKenzie and Wallace 1954).

Available N in soils was extracted by shaking the soil for 1 h with 2 M KCl at a 1 : 10 dry soil : solution ratio and measured by the Kjeldahl method (Keeney 1982). Available P was extracted by using the anion exchange resin method after Kouno *et al*. (1995), and the P concentration was determined colourimetrically (Murphy and Riley 1962). Inorganic N and P in the leachate were also determined by the distillation method and the Murphy and Riley method, respectively.

Statistical analyses

The data of cumulative soil respiration on day 23 and the nutrient loss in the leachate as an average of three sampling times were analysed by one-way ANOVA. Water-soluble OC concentration

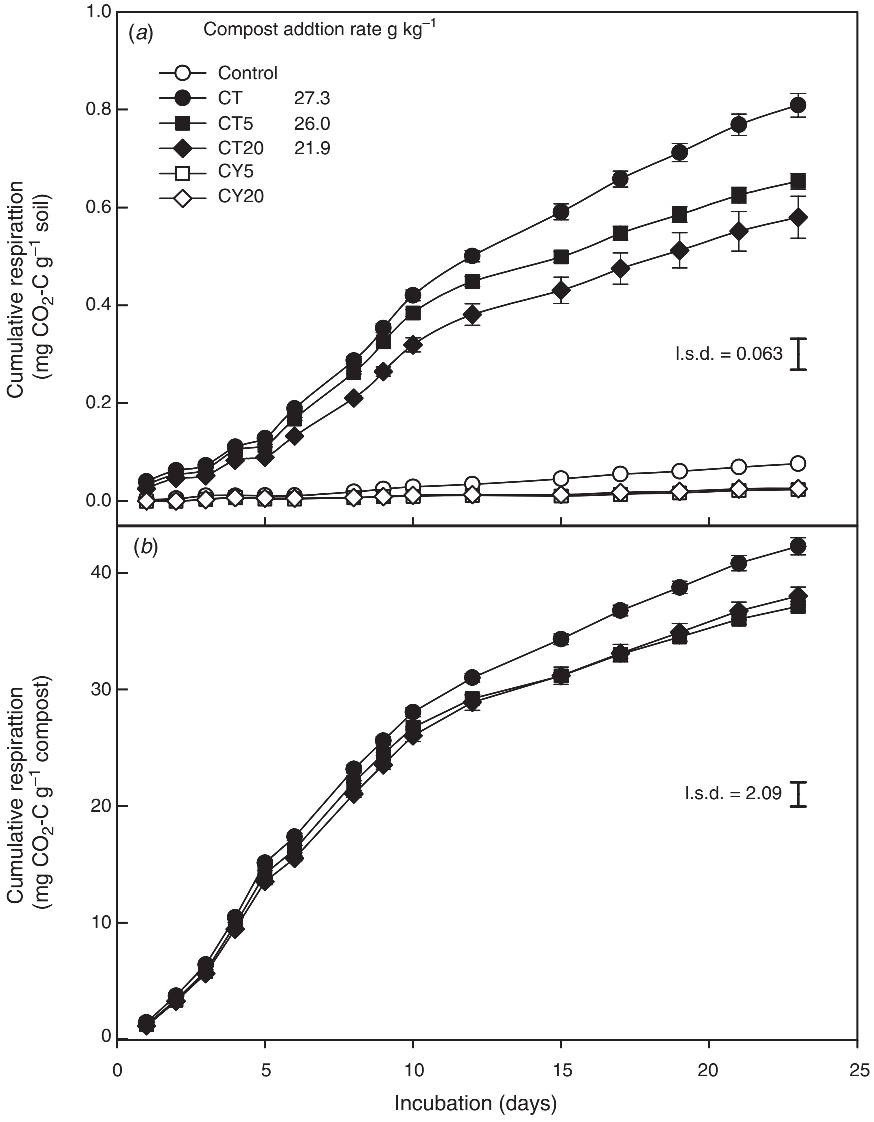

Fig. 1. Cumulative respiration (*a*) per g soil or, where applicable, (*b*) per g compost, of non-amended sandy soil (control) or soil amended with only compost (CT), with compost mixed with the fine-textured soil at 5% (CT5) and 20% (CT20), or with only fine-textured soil at 5% (CY5) and 20% (CY20). The l.s.d. ($P = 0.05$) at day 23 is presented; $n = 4$, ± s.e.

in soil and the leachate, inorganic N and P in the leachate, and available N and P in soil were analysed by two-way ANOVA (treatments × sampling times). Differences between means were compared by Duncan analysis ($P \leq 0.05$) using GENSTAT for Windows, 11th edn (GENSTAT 2005).

Results

Respiration

Compared with the non-amended sandy soil, cumulative respiration (mg CO_2-C g^{-1} soil) increased significantly with compost amendment alone (CT) or compost mixed with the fine-textured soil (CT5, 20; Fig. 1*a*), whereas addition of the fine-textured soil alone (CY5, CY20) had no effect on cumulative respiration (Fig. 1*a*). Compared with the sandy soil amended with compost only, addition of fine-textured soil to compost (at 5 or 20%) reduced cumulative respiration per g soil (Fig. 1*a*) and also per g compost (Fig. 1*b*).

Water-soluble organic carbon

Compared with the non-amended sandy soil, compost addition (CT treatments) increased the water-soluble OC concentration in the leachate and soil, particularly on day 1, whereas the addition of fine-textured soil alone had no effect (CY treatments) (Fig. 2*a*, *b*). Compared with compost alone (CT), addition of the fine-textured soil to compost (CT5 and CT20) reduced the

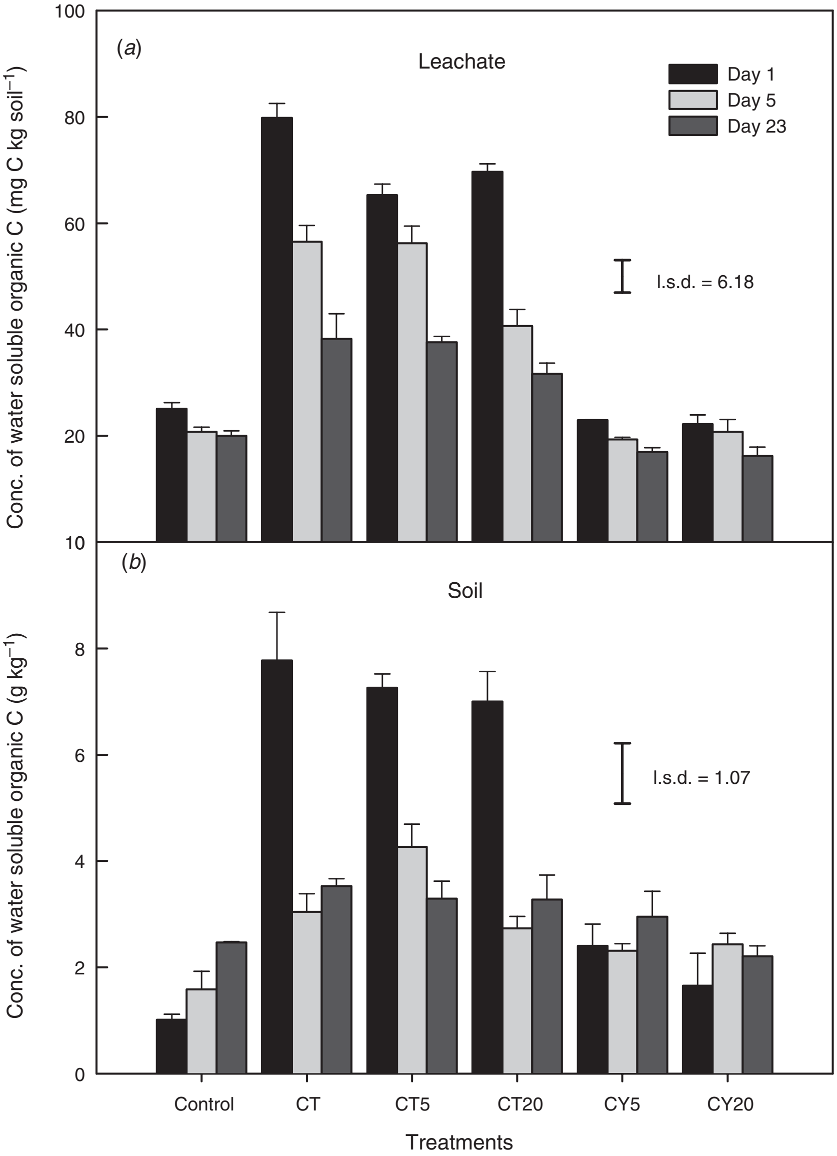

Fig. 2. Water-soluble organic carbon concentration in (*a*) the leachate and (*b*) the soil, for non-amended sandy soil (control) or soil amended with only compost (CT), with compost mixed with the fine-textured soil at 5% (CT5) and 20% (CT20), or with only fine-textured soil at 5% (CY5) and 20% (CY20) at day 1, 5, and 23. The l.s.d. ($P = 0.05$) for the interaction treatments × sampling times is presented; $n = 4$, ± s.e.

water-soluble OC concentration in the leachate, with the stronger effect in CT20 (Fig. 2*a*), but had no effect on the concentration of water-soluble C in the soil (Fig. 2*b*). However, after subtracting the water-soluble C concentration in the leachate of the non-amended sandy soil (control) from that of the compost-amended soils, the concentration of water-soluble organic C in the leachate was similar with compost alone and compost amended with fine-textured soil (Table 2).

Inorganic N in the leachate and available N

The concentration of inorganic N (NO_3^--N and NH_4^+-N) in the leachate varied with sampling time and did not differ between

Table 2. Nutrient loss in leachate (Nut_{leach} calculated according to Eqn 1) from soil amended with only compost (CT) or compost mixed with fine-textured soil at 5% and 20% (w/w) (CT5 and CT20)

Data are the average of three sampling times and presented as percentage of initial total C, N, and P concentrations in added compost of each treatment. Within columns, values followed by the same letter are not significantly different at $P = 0.05$ ($n = 4$). n.s., Not significant

Treatments	Carbon	Nitrogen	Phosphorus
CT	0.97 ± 0.02	0.65b ± 0.03	1.15b ± 0.02
CT5	0.86 ± 0.05	0.49ab ± 0.11	1.12b ± 0.05
CT20	0.85 ± 0.03	0.23a ± 0.06	0.75a ± 0.04
l.s.d. ($P = 0.05$)	n.s.	0.24	0.13

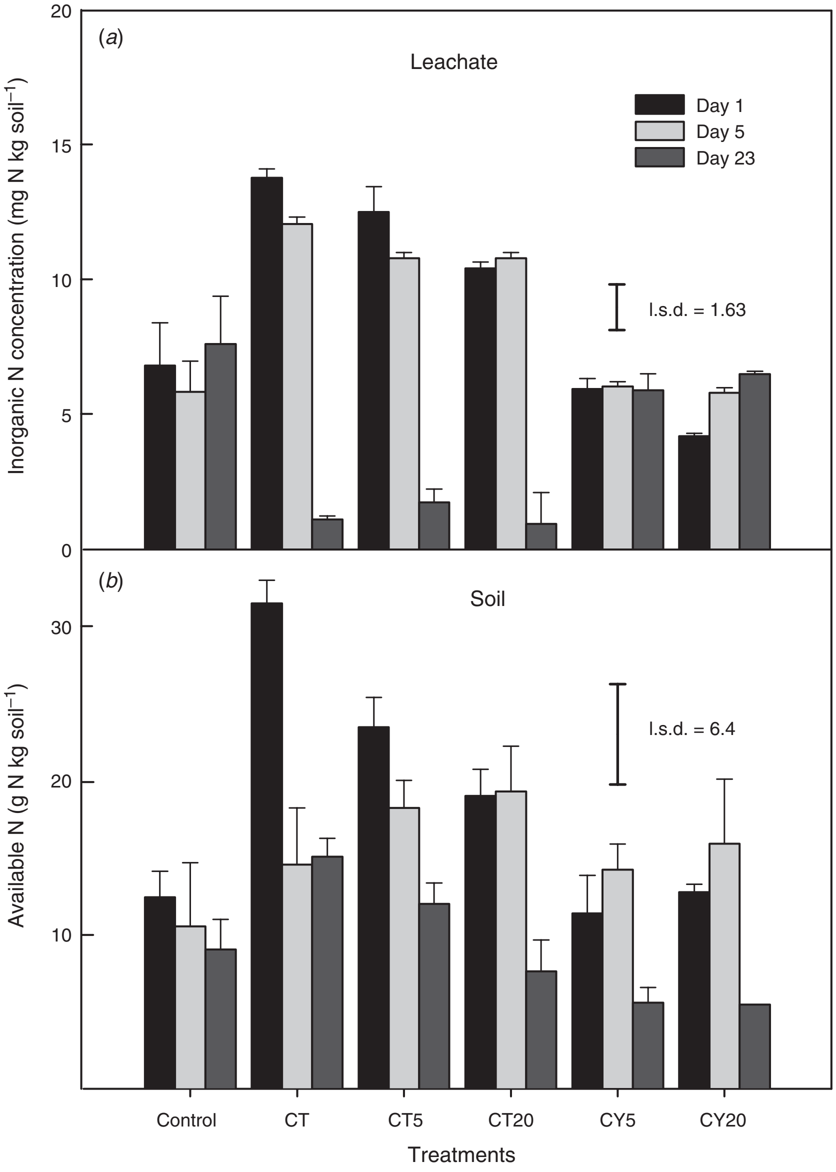

Fig. 3. (*a*) Inorganic nitrogen concentration in the leachate and (*b*) available N in the soil, for non-amended sandy soil (control) or soil amended with only compost (CT), with compost mixed with the fine-textured soil at 5% (CT5) and 20% (CT20), or with only fine-textured soil at 5% (CY5) and 20% (CY20) at days 1, 5, and 23. The l.s.d. ($P = 0.05$) for the interaction treatments × sampling times is presented; $n = 4$, ± s.e.

the non-amended sandy soil and sandy soil with the fine-textured soil (CY treatments) (Fig. 3*a*). Compared with the non-amended sandy soil, compost and compost mixed with the fine-textured soil (CT treatments) increased the concentration of inorganic N in the leachate on days 1 and 5, but decreased it on day 23 (Fig. 3*a*). However, when expressed as a percentage of the initial N concentration of the compost (Table 2), the addition of fine-textured soil to compost (CT5 and CT20) significantly decreased the inorganic N concentration in the leachate compared with compost alone. Compared with the non-amended sandy soil or sandy soil with fine-textured soil alone, compost amendment without or with addition of fine-textured soil increased the concentration of available N in the soil on days 1 and 23, but not on day 5 (Fig. 3*b*).

Phosphorus in the leachate and available P

Compared with the non-amended sandy soil, compost amendment with or without fine-textured soil (CT treatments) increased the concentration of P in the leachate and the available P concentration in the soil, whereas the addition of fine-textured soil alone had no effect (CY treatments) (Fig. 4). Compared with compost alone, the addition of fine-textured soil to compost at 20% (CT20) significantly decreased the concentration of P in

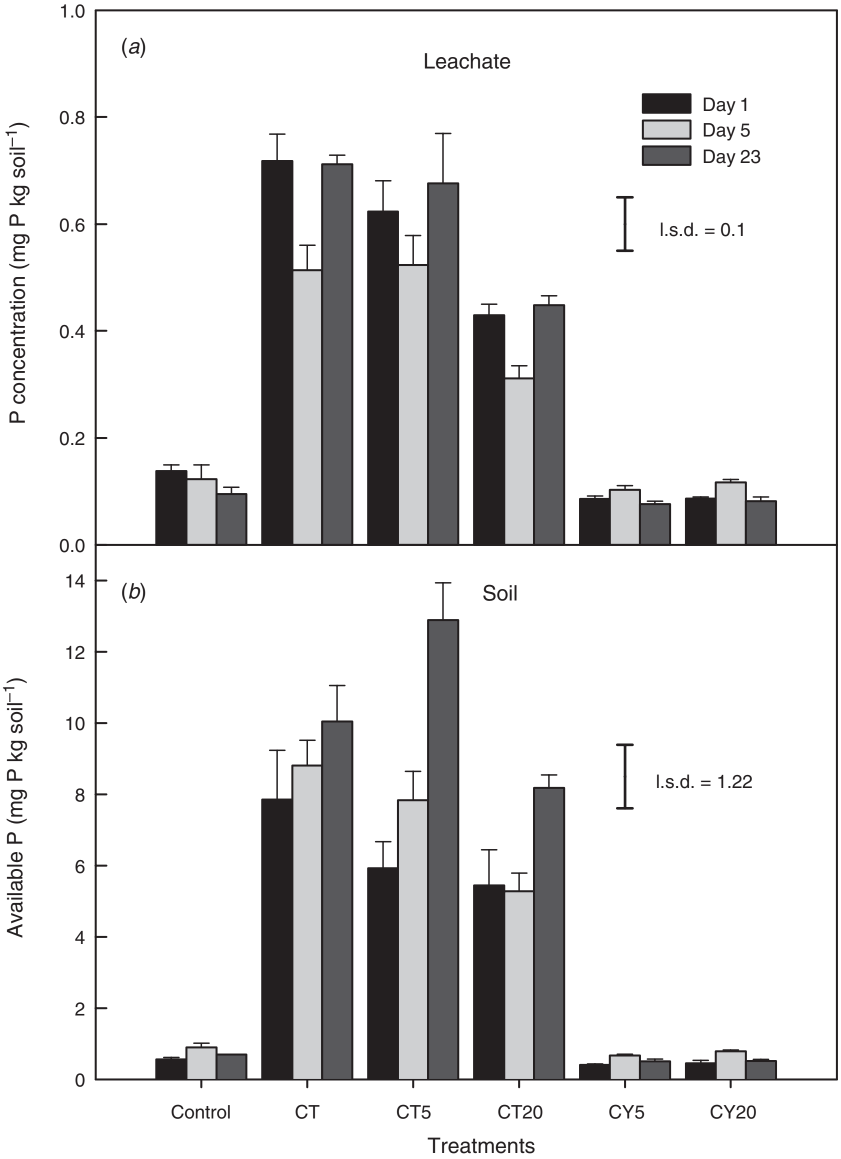

Fig. 4. (*a*) Phosphorus concentration in the leachate and (*b*) available P in the soil, for non-amended sandy soil (control) or soil amended with only compost (CT), with compost mixed with the fine-textured soil at 5% (CT5) and 20% (CT20), or with fine-textured soil at 5% (CY5) and 20% (CY20) at days 1, 5, and 23. The l.s.d. ($P = 0.05$) for the interaction treatments × sampling times is presented; $n = 4$, ± s.e.

the leachate and the concentration of available P in the soil (Table 2, Fig. 4).

Discussion

This study showed that adding fine-textured soil to compost reduced cumulative respiration and N and P concentrations in the leachate, but did not affect available N and P concentrations in the soil.

In agreement with previous studies (Mamo *et al*. 1999; Basso and Ritchie 2005), compost amendment increased the concentrations of water-soluble OC, inorganic N, and P in the leachate (Figs 2*a*, 3*a*, 4*a*). This can be explained by the addition of available nutrients with the compost (Hadas and Portnoy 1994), and also by mineralisation of the compost during the experimental period. Addition of the fine-textured soil alone had little effect on nutrient availability and leaching due to its low C, N, and P concentrations (Table 1). Mixing of clay soil with the sandy soil can reduce aeration and respiration (Khalil *et al*. 2005), but in the present study, the addition of the fine-textured soil alone to sandy soil did not reduce cumulative respiration compared with the non-amended sandy soil (Fig. 1). This may be due to its relatively low clay content (34%) compared with the clay soil used in the study by Khalil *et al*. (2005), which had higher clay content (40%).

The addition of the fine-textured soil to compost reduced leaching of N and P, with stronger effect at 20% (w/w) (Table 2, Figs 3*a*, 4*a*), but had no effect on the concentration of water-soluble C in the leachate (Table 2). The reduced leaching can be explained by the greater surface area of the fine-textured soil compared with the sandy soil (Table 1). The clay in the fine-textured soil can absorb nutrients and make organic matter less available to microbes through sorption and occlusion (Baldock 2007). This is also evident in the reduction of cumulative respiration by addition of the fine-textured soil to compost when expressed per g compost (Fig. 1*b*). The reduced cumulative respiration per g soil by addition of fine-textured soil to compost could be explained by the smaller amount of compost added. However, the reduction of cumulative respiration per g compost shows that the addition of fine-textured soil reduced the availability of the organic matter in the compost to soil microbes (Sørensen 1972). But addition of the fine-textured soil to compost did not reduce soil nutrient availability (Figs 2*b*, 3*b*, 4*b*). This suggests that, although clay particles can reduce nutrient leaching by sorption, the sorbed N and P remain at least partly available to plants.

Our results show that addition of fine-textured soil to compost can reduce nutrient leaching from compost and thereby the risk of eutrophication. However, this was only a short-term experiment. Further research is required to investigate the long-term effect of different clay mineralogy addition to compost on nutrient leaching and plant growth.

Acknowledgements

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CHAPTER 6

RETENTION AND LOSS OF WATER EXTRACTABLE CARBON IN SOILS: EFFECT OF CLAY PROPERTIES

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STATEMENT OF AUTHORSHIP

Retention and loss of water extractable carbon in soils: effect of clay properties

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Performed experiment, analyses of soil and compost samples, data analysis and interpretation, wrote manuscript, acted as a corresponding author.

I hereby certify that the statement of contribution is accurate.

Signed: Date: 03/10/2013

Petra Marschner

Supervised development of work, data interpretation and manuscript evaluation and correction

I hereby certify that the statement of contribution is accurate and I give permission for the inclusion of the paper in the thesis.

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Retention and loss of water extractable carbon in soils: Effect of clay properties

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HIGHLIGHTS

- Little is known about which clay properties are important for retention and loss of water extractable C (WEOC).
- Clay with higher native TOC and lower Fe/Al concentrations sorbed less and lost more WEOC.
- Clays with low TOC and high Fe/Al concentrations had a high WEOC retention capacity.
- Retention of WEOC was not related to clay mineralogy, CEC, and exchangeable Ca concentration.

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ABSTRACT

Clay sorption is important for organic carbon (C) sequestration in soils, but little is known about the effect of different clay properties on organic C sorption and release. To investigate the effect of clay content and properties on sorption, desorption and loss of water extractable organic C (WEOC), two experiments were conducted. In experiment 1, a loamy sand alone (native) or mixed with clay isolated from a surface or subsoil (78 and 96% clay) resulting in 90, 158 and 175 g clay kg^{-1} soil. These soil treatments were leached with different WEOC concentrations, and then CO_2 release was measured for 28 days followed by leaching with reverse osmosis water at the end of experiment. The second experiment was conducted to determine WEOC sorption and desorption of clays isolated from the loamy sand (native), surface soil and subsoil. Addition of clays isolated from surface and subsoil to sandy loam increased WEOC sorption and reduced C leaching and cumulative respiration in percentage of total organic C and WEOC added when expressed per g soil and per g clay. Compared to clays isolated from the surface and subsoil, the native clay had higher concentrations of illite and exchangeable Ca^{2+}, total organic C and a higher CEC but a lower extractable Fe/Al concentration. This indicates that compared to the clay isolated from the surface and the subsoil, the native clay had fewer potential WEOC binding sites because it had lower Fe/Al content thus lower number of binding sites and the existing binding sites are already occupied native organic matter. The results of this study suggest that in the soils used here, the impact of clay on WEOC sorption and loss is dependent on its indigenous organic carbon and Fe and/or Al concentrations whereas clay mineralogy, CEC, exchangeable Ca^{2+} and surface area are less important.

1. Introduction

Dissolved organic carbon (DOC), derived from microbial activity, root exudates, leachate of canopy and leaf litter, accounts for only a small proportion of total soil carbon and is the most mobile and bioavailable fraction of soil organic matter (Marschner and Kalbitz, 2003; McDowell, 2003). DOC has an important role in ecosystems because it is an easily accessible carbon source for microbes (Burford and Bremner, 1975; Meyer et al., 1987). The DOC concentration retained within the soil–water system depends on supply and adsorption capacity of the soil (Nodvin et al., 1986). Retention and mobility of DOC are influenced by soil properties such as pH, metal concentrations (e.g. amorphous Fe and Al oxides) (Kaiser and Guggenberger, 2000; Kaiser et al., 1996), clay and/or soil minerals (Gonzalez and Laird, 2003; Kaiser and Zech, 2000; McDowell, 2003).

Clay can reduce accessibility of the organic matter to soil microbes by sorption and occlusion in aggregates (Nelson et al., 1997). For example, Shi and Marschner (2013) found that subsoil clay addition to sandy soil reduced cumulative respiration and extractable C concentration. Clay-sized particles can bind organic matter via cations and oxides covering the clay surface (Amato and Ladd, 1992; Nelson et al., 1997). Sorption of organic matter to clay is influenced by surface area (Kaiser et al., 1996; Nelson et al., 1997), cation exchange capacity (CEC) (Amato and Ladd, 1992) and clay mineralogy (Benke et al., 1999; Nelson et al., 1997; Ransom et al., 1998). Organic C is preferentially sequestered in smectite-rich sediments compared to clays fraction dominated by chlorite (Ransom et al., 1998). Illite has a lower DOC sorption capacity

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than smectite and kaolinite (Nelson et al., 1997; Ransom et al., 1998) and Benke et al. (1999) showed that C sorption increased in the following order: kaolinite < haematite < goethite. However, organic C sorption also seems to be related to the native organic matter content because there is a negative correlation between DOC retention and organic matter content of subsoil (Jardine et al., 1989).

The previous studies mentioned above focused on the effect of clay particle size, type and content on C retention (Amato and Ladd, 1992; Gonzalez and Laird, 2003; Nelson et al., 1997), but little is known about the link between clay properties and leaching, sorption and desorption of water extractable organic C (WEOC). The aim of this study was to determine if addition of clays isolated from two different soils to a loamy sand affects leaching and sorption of WEOC derived from compost and how this is related to clay properties.

2. Materials and methods

2.1. Soils

A loamy sand (0–15 cm) was collected from Monarto, South Australia (35°6′S, 139°37′E). The region is semi-arid with a Mediterranean climate. Surface soil (0–15 cm, 51% sand, 15% silt and 34% clay) was collected in Brinkley, South Australia (35°2′S, 139°2′E) and a subsoil (30–50 cm, 18% sand, 20% silt and 62% clay) from the Agricultural Reserve, La Trobe University, Bundoora, Victoria, Australia (37°72′S, 145°05′E). All soils were air-dried and sieved to <2 mm (Table 1).

2.2. Clay isolation

To isolate the clay fraction, the soils were dispersed in reverse osmosis water at 1:5 soil: water ratio and shaken for 24 h. Then the suspension was transferred to a bucket and left to settle for 16 h. The <2 μm clay fraction was collected by siphoning off the top 22 cm of the soil suspension. The settling time (16 h) and the height of the soil suspension (22 cm) were selected based on Stokes' law (Jackson, 2005). Then, the isolated clay was dried at 50 °C (Table 1).

Table 1
Physical, chemical and mineralogical properties of loamy sand and clays isolated from the loamy sand (native), surface and subsoil clay soils (n = 3).

Properties	Loamy sand	Native clay	Surface clay	Subsoil clay	LSD ($P \leq 0.05$)
Particle size (%)					
Sand	84	0	0	0	
Silt	7	4	22	4	
Clay	9	96	78	96	
Electrical conductivity$_{1:5}$ (μS cm^{-1})	59	1355	336	363	
pH	7.3	7.4	8.7	5.7	
Water holding capacity (g kg^{-1})	50.1	615.0	685.4	651.5	
Total organic C (g kg^{-1})	2.0^a	30.5^c	6.3^b	7.7^b	1.3
Water soluble organic C (mg kg^{-1})	19^a	205^c	75^{ab}	94^b	49
Cation exchange capacity (cmol$_c$ kg^{-1})	na	25.1^b	15.0^a	12.9^a	5.7
Water extractable Fe (mg kg^{-1})	na	5.6^a	33.5^c	24.6^b	3.0
Water extractable Al (mg kg^{-1})	na	8.4^a	37.4^c	33.2^b	6.0
Surface area (m^2 g^{-1})	na	315	168	322	ns
Total organic C: Surface area (μg m^{-2})	na	97^b	38^a	24^a	37
Exchangeable cation (cmol$_c$ kg^{-1})					
Ca	na	13.5^b	8.1^a	4.9^a	3.0
Mg	na	4.1	3.2	4.3	ns
Na	na	1.3^c	0.6^a	0.9^b	0.2
K	na	7.4^b	3.6^a	3.8^a	1.9
Mineralogy (%, wt) of <2 μm clay fraction[1]					
Illite		45–50	15–20	20–25	
Kaolinite		25–30	7–12	35–40	
Smectite		<5	5–10	2–5	

[1] Dominant minerals. na is not applicable. LSD is least significant difference at $P \leq 0.05$. ns is not significant. Within rows, means followed by the same letter are not significantly different ($P > 0.05$).

2.3. Water extractable organic carbon

Water extractable organic matter was extracted from fine grade garden compost by shaking 1 g of compost with 6 ml reverse osmosis water overnight at 4 °C. The suspension was centrifuged at 14758 ×*g* for 10 min and filtered (#42 Whatman™) and then stored at −20 °C until further use. We use the term water-extractable organic carbon (WEOC) because some of the C in the water extract may be colloidal, not dissolved. The organic C concentration of the extract was 1023 mg l^{-1}. For experiments, the WEOC stock was thawed at room temperature and then diluted before being immediately added to the soils or isolated clays. The WEOC concentration in all extracts was measured as described below.

2.4. Experimental design

This study included two experiments. An experiment in which WEOC was added to soil cores filled with loamy sand alone or loamy sand with isolated clays. WEOC in the leachate and soil respiration were measured. In the second experiment, sorption of WEOC to isolated clays was determined in a batch sorption experiment.

2.4.1. WEOC leaching experiment

There were three soil treatments: unamended loamy sand (native) or amended with the clay isolated from the surface soil (surface) or the subsoil (subsoil) at a rate of 98.1 g kg soil^{-1} to increase the clay content from 9 to 18% assuming that the isolated fraction contained only clay. However, particle size analysis of these fractions showed that the clay content was 78% and 96% for the surface and subsoil clay, respectively (Table 1). Therefore the actual clay content of treatments was 90, 158 and 175 g clay kg^{-1} soil for the unamended loamy sand (native) and soil amended with clays isolated from surface and subsoil, respectively. Reverse osmosis water was added to reach 60% of water holding capacity. This water content was chosen because it had been shown to result in maximal soil respiration in soils with 10–20% clay (Setia et al., 2011a). The moist soils were pre-incubated for two weeks at 25 °C to reactivate the microbes. Throughout the pre-incubation and the subsequent incubation period, water was added on mass basis to maintain 60% of water holding capacity.

The pre-incubated soils (equivalent to 30 g dry soil) were filled to polyvinyl cores (PVC, 3.7 cm width and 5.0 cm height) with a nylon mesh base (0.75 μm, Australian Filter Specialist) and packed to a bulk density of 1.22 g cm^{-3}. The mesh was covered with filter paper (#42 Whatman™) to minimize loss of clay-sized particles during leaching. The cores were placed vertically in plastic funnels with the mesh facing down. 30 ml each of the six water extractable organic C (WEOC$_{add}$) concentrations was added to the cores (0, 252, 494, 712, 865 and 1023 mg C l^{-1} or per unit soil weight 0, 252, 494, 712, 865 and 1023 mg C kg soil^{-1}) which were then kept overnight at 4 °C to collect the leachate (with three replicates per WEOC treatment and soil). This range was chosen because a preliminary experiment showed that the maximum WEOC sorption of the loamy sand was about 800 mg C kg^{-1} soil. The leachate was collected and analysed for WEOC (WEOC$_{leachate}$) as described below. The volume of the leachate was 22 ml for all treatments.

2.4.1.1. Calculations.

The total organic C (TOC$_{total}$) of the soil treatments is the sum of indigenous TOC of the soils or clays and the different concentrations of WEOC added (Eq. (1)): (WEOC$_{add}$).

$$\mathrm{TOC_{total}} = \mathrm{TOC} + \sum\nolimits_{i=0}^{n} \mathrm{WEOC_{add}} \tag{1}$$

where, i–n are the different added WEOC concentrations (g C kg^{-1}).

The amount of WEOC leached (WEOC$_{leach}$) from WEOC added was calculated by the difference between WEOC in the leachate after addition of the compost extracts (WEOC$_{com}$) (252, 494, 712, 865 and

1023 mg C kg^{-1}soil) and WEOC in the leachate from the soils to which only water was added ($WEOC_{con}$) expressed either per kg soil (Eq. (2)):

$$WEOC_{leach} = WEOC_{com} - WEOC_{con}. \tag{2}$$

To take into account differences in clay content among soil treatments and therefore WEOC added per kg clay, WEOC added was normalised by clay content and expressed as percentage of added WEOC ($WEOC_{leach}$) concentrations of added WEOC per kg clay:

$$WEOC_{leach}(\%) = \frac{(WEOC_{com} - WEOC_{con})}{WEOC_{add}} \times 100. \tag{3}$$

Sorption of WEOC added ($WEOC_{sorb}$) was calculated as the difference between WEOC added with the compost extracts (g kg^{-1} soil) and the WEOC in the leachate ($WEOC_{leachate}$) expressed either per kg soil or, after normalisation of added WEOC by clay content, as percentage.

$$WEOC_{sorb} = WEOC_{add} - WEOC_{leachate} \tag{4}$$

$$WEOC_{sorb}(\%) = \frac{WEOC_{add} - WEOC_{leachate}}{WEOC_{add}} \times 100. \tag{5}$$

2.4.1.2. Respiration. The leached cores were placed into 0.25 l glass jars which were then sealed with gas tight lids equipped with septa to allow quantification of the CO_2 concentration in the headspace. The jars were incubated in the dark at 22 to 25 °C for 28 days during which the CO_2 concentration was measured every 1–2 days (see below). To dry the soil after leaching, a small pouch containing self-indicating silica-gel (BDH chemicals) was placed into the jars and changed daily until after 10 days, the soil water content had reached 60% of water holding capacity. This water content was maintained until day 28 by checking the weight of the cores every second day and adding reverse osmosis water if necessary.

Respiration (CO_2 release) was measured by quantifying the headspace CO_2 concentrations within each jar with a Servomex 1450 infrared gas analyser (Servomex, UK). Due to the decline in respiration rates over time and the upper detection limit of the gas analyser, the CO_2 concentration was measured daily in the first 10 days and then every second day until end of the experiment (28 days). For each measurement period, an initial measurement was taken immediately after closing the jars after refreshing the air in the jars (T_o). After the second measurement (T_1), the jars were opened to refresh the headspace in the jars by a fan. The CO_2 evolved from each sample was calculated as the difference between T_1 and T_o for each measurement period. The relationship between CO_2 concentration and detector response was determined by linear regression obtained by injecting known amounts of CO_2 into jars similar to those used for the samples. This regression was then used to calculate the CO_2 concentration in the jars with soils (for details about the calculation see Setia et al. (2011b)). Cumulative CO_2–C (respiration) is expressed per kg soil, clay or as percentage of total organic C and WEOC sorbed (TOC + $WEOC_{sorb}$).

To determine the WEOC remaining at the end of experiment, 30 ml of reverse osmosis water was added on day 28 and the leachate collected after 16 h at 4 °C. The volume of the leachate was 24 ml for all treatments. The leachate was analysed for WEOC ($WEOC_{loss}$) and the total C loss (Total C_{loss}) during the experiment was calculated as (Eq. (6))

$$\text{Total}\, C_{loss}(\%) = \frac{WEOC_{leachate} + \text{Respiration} + WEOC_{loss}}{TOC_{total}} \times 100. \tag{6}$$

2.4.2. WEOC sorption by isolated clays

In this experiment, six WEOC concentrations (0, 254, 508, 685, 819, 900 mg l^{-1}) were used. 30 ml of WEOC extracts was added to 3 g clay which is equivalent to 3.13, 3.85, 3.13, 3.45 and 3.13 g of the clay fraction isolated from the loamy sand (native), the surface, subsoil clay or a mixture of native plus surface clay (mixture 1, 1:1) or native plus subsoil clay (mixture 2, 1:1), respectively. These mixtures reflect the ratios of native and added clays in the leaching experiment. The suspensions were shaken on an end-over-end shaker for 24 h at 4 °C, followed by centrifuging at 14758 ×g for 10 min. The amount of WEOC sorbed ($WEOC_{sorb}$) is the difference between initial WEOC concentration and that in the supernatant.

To determine desorption, the residual soil pellet from the sorption experiments was suspended in 30 ml of reverse osmosis water followed by shaking and centrifuging as described above.

2.5. Analyses

Soil texture was determined by the hydrometer method as described by Gee and Or (2002). The pH and EC were determined in a 1:5 soil:water extract after 1 h end-over-end shaking at 25 °C (Rayment and Higginson, 1992). The soil water holding capacity was determined using a sintered glass funnel connected to 100 cm water column (matric potential = −10 kPa) (Wilke, 2005). The mineralogy of the <2 μm clay fraction was measured by X-ray diffraction (Brindley, 1980). Total organic carbon was determined by wet oxidation and titration (Walkley and Black, 1934).

The concentration of water extractable Fe and Al was measured in a 1:5 soil:water suspension after 1 h end-over-end shaking of 5 g clays in 25 ml of deionised water (Table 1). The concentration of exchangeable cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) and cation exchange capacity (CEC) was determined after the soluble salts were removed by washing 5 g soil with 25 ml of ethanol (60%) as described in Rayment and Lyons (2011). The concentrations of extractable Fe and Al and exchangeable

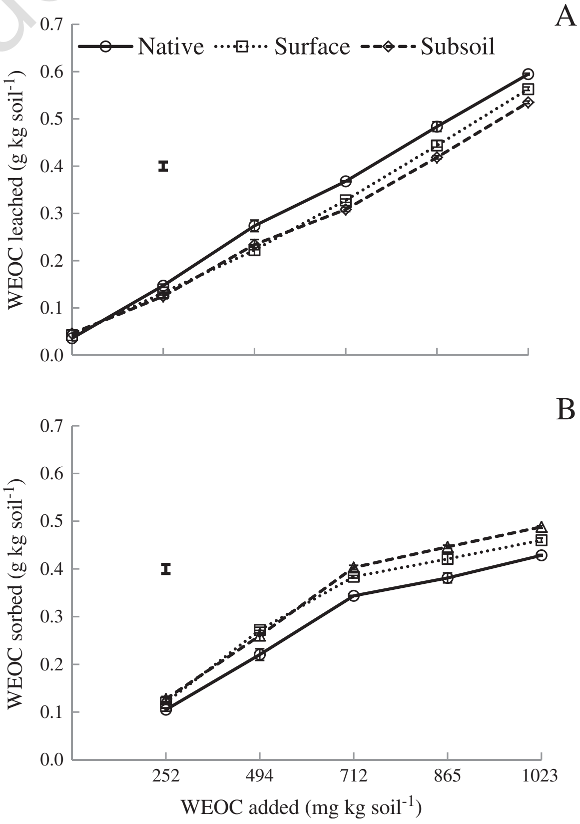

Fig. 1. Water extractable organic C (WEOC) leached after addition of 0–1023 mg WEOC from compost extract per kg soil to the loamy sand alone (native) or mixed with clay isolated from surface (surface) or subsoil (subsoil) at the beginning of the experiment ($WEOC_{leach} = WEOC_{com} - WEOC_{con}$) (A) and calculated WEOC sorption ($WEOC_{sorb} = WEOC_{add} - WEOC_{leachate}$) (B). Single vertical lines indicate least significant difference (treatment × WEOC concentration); n = 3 ± standard error.

Na^+, K^+, Ca^{2+} and Mg^{2+} in the soil extracts were measured by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). Cation exchange capacity was calculated according to Hendershot and Duquette (1986).

The WEOC concentration was determined by $K_2Cr_2O_7$ and H_2SO_4 oxidation, followed by titration with acidified $(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O$ (Anderson and Ingram, 1993) with sucrose solution as a standard. All data was calculated as g WEOC per kg soil or clay.

2.6. Statistical analysis

Chemical and physical properties of loamy sand and isolated clays were analysed by one way analysis of variance. The WEOC and cumulative respiration data were analysed by two way analysis of variance (3 treatments × 6 WEOC concentrations). There were 3 replicates per treatment and differences between means were compared by Duncan test ($P \leq 0.05$) with GenStat® 11th (GenStat® for Windows® 11th Edition 2005).

3. Results

3.1. Soil and clay properties

The isolated clay varied in mineralogy. Illite was the dominant clay mineral in the clay from the loamy sand whereas kaolinite dominated in the clay from the subsoil (Table 1). Clay from the loamy sand contained about twice as much illite than the clays from surface and subsoil (Table 1). All isolated clays had higher electrical conductivity, water holding capacity, TOC and WEOC concentrations than the loamy sand (Table 1). The clay isolated from the loamy sand had higher concentrations of TOC, TOC: surface area ratio and exchangeable cations and CEC, but lower concentrations of water extractable Fe and Al than the clays isolated from surface or subsoil.

3.2. WEOC leaching experiment

The concentrations of WEOC in the leachate ($WEOC_{leachate}$) and the proportion of added WEOC that was leached ($WEOC_{leach}$) increased with increasing concentration of added WEOC (Fig. 1A and Table 2). Compared to the loamy sand alone (native), the addition of clays isolated from surface soil or subsoil reduced WEOC concentration in the leachate (Fig. 1A). At high concentrations of WEOC added (>712 mg WEOC kg^{-1} soil), the addition of subsoil clay reduced WEOC leaching compared to surface clay (Fig. 1A). When WEOC added was normalised by clay content, the percentage of WEOC added that was leached decreased in the following order in native > surface > subsoil clay (Table 2).

The concentrations of WEOC sorbed per kg soil ($WEOC_{sorb} = WEOC_{add} - WEOC_{leachate}$) increased with increasing concentration of WEOC added in all soil treatments (Fig. 1B). The loamy sand alone (native) sorbed less WEOC (per kg soil and in percentage of added WEOC per g clay) than when amended with clay isolated from surface or subsoil (Fig. 1B, Table 2).

The addition of isolated clay to the loamy sand did not reduce cumulative respiration per kg soil (Fig. 2A). However, when expressed as percentage of TOC + WEOC sorbed, cumulative respiration of loamy sand alone (native) was higher than when amended with either surface or subsoil clay (Fig. 2B and Table 2). The increase in cumulative respiration with increasing concentration of WEOC added was greater in the loamy sand alone (native) than in the loamy sand amended with surface or subsoil clay.

When the cores were leached with reverse osmosis water at the end of the experiment, the WEOC concentration in the leachate ($WEOC_{loss}$) and total C loss ($WEOC_{leachate}$ + Respiration + $WEOC_{loss}$) per kg soil did not differ among the treatments (Fig. 3A and B). However, when expressed as percentage of TOC_{total} (TOC + WEOC sorbed) $WEOC_{loss}$ and total C loss were greater in the loamy sand alone (native) than when amended with clay isolated from surface or subsoil (Table 2 and Fig. 3C). With increasing concentration of WEOC added, total C loss

Table 2

Percentage of water extractable organic C (WEOC) leached ($WEOC_{leach}$), sorbed ($WEOC_{sorb}$), respired (Cumulative CO_2), lost ($WEOC_{loss}$) and total organic C loss (Total C_{loss}) for loamy sand alone (native clay) or mixed with surface or subsoil clay soil ($n = 3$). The data are normalised by clay content. For explanations of the terms see Materials and methods section.

Added WEOC (g C kg $soil^{-1}$)	$WEOC_{leach}$ (% of $WEOC_{add}$)	$WEOC_{sorb}$ (% of $WEOC_{add}$)	Cumulative CO_2 (% of TOC + $WEOC_{sorb}$)	$WEOC_{loss}$ (% of TOC remain[1])	Total C_{loss} (% of TOC + $WEOC_{add}$)
Native					
0					8.3
252	60.6	19.9	10.5	0.56	18.0
494	66.1	24.0	18.0	1.29	31.3
712	64.1	29.0	16.3	1.54	33.3
865	71.1	23.4	12.3	1.50	37.9
1023	75.0	20.2	21.9	1.83	46.2
Surface					
0					3.9
252	45.1	32.4	6.9	0.30	10.0
494	46.8	42.1	9.8	0.30	15.0
712	51.6	40.7	8.6	0.74	16.1
865	59.7	33.9	11.4	0.71	21.1
1023	65.5	29.2	11.6	0.83	23.5
Subsoil					
0					3.6
252	40.9	35.4	5.9	0.34	8.6
494	49.7	38.2	7.5	0.34	12.3
712	48.2	43.4	10.2	0.44	16.5
865	56.3	36.8	11.3	0.43	19.4
1023	62.4	31.7	11.4	0.68	21.5
	P (LSD)	*P* (LSD)	*P* (LSD)	*P* (LSD)	*P* (LSD)
Clay (C)	(2.1)***	(2.1)***	(1.8)***	(0.13)***	(1.6)***
WEOC (W)	(2.7)***	(2.7)***	(2.4)***	(0.18)***	(2.3)***
C × W	ns	ns	ns	(0.3)**	(3.9)***

ns, **, *** not significant or significant at $P \leq 0.01$, or $P \leq 0.001$, respectively.

LSD is least significant difference.

[1] TOC remain = $TOC_{total} - WEOC_{leach}$ − Respiration. TOC is total organic C.

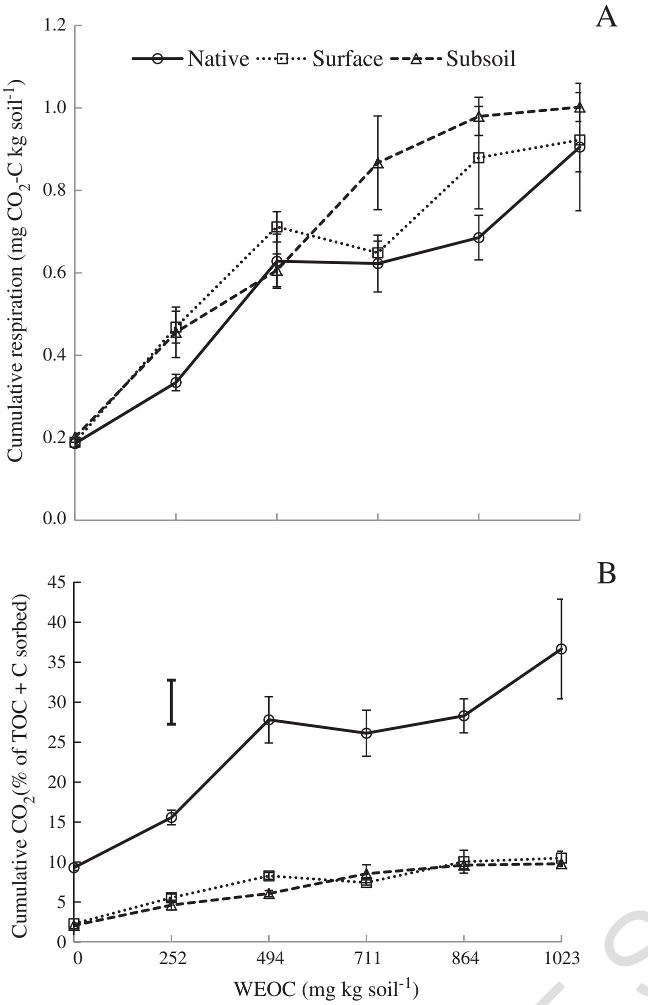

Fig. 2. Cumulative respiration in mg CO_2–C kg soil^{-1} (A) or in percentage of TOC + WEOC sorbed (B) over 28 days after addition of 0–1023 mg WEOC from compost extract per kg soil to the loamy sand alone (native) or mixed with clay isolated from surface (surface) or subsoil (subsoil). Single vertical lines indicate least significant difference (clay treatment × WEOC concentration); n = 3 ± standard error.

of the loamy sand alone (native) increased sharply, whereas when amended with surface or subsoil clay $WEOC_{loss}$ and total C_{loss} increased gradually (Fig. 3C and Table 2).

3.3. Sorption experiment with isolated clays

The release of soil WEOC (treatment without addition of WEOC) was greater from the clay isolated from the loamy sand (native) than the other two clays (Fig. 4A). The concentration of WEOC sorbed increased with increasing concentration of added WEOC and reached a maximum at 8.2 g C kg clay^{-1} for the native and surface clay and their mixtures, whereas the sorption maximum of the subsoil clay was not reached (Fig. 4A). WEOC sorption decreased in the following order: subsoil clay > surface > mixture 2 > mixture 1 > native clay. In contrast, desorption (in percentage of sorbed WEOC) was greater from the native clay than from the surface and subsoil clay and the mixtures (Fig. 4B).

4. Discussion

This study showed that clays differ in sorption and desorption of WEOC and organic C availability to soil microbes. The clay from the loamy sand had the lowest sorption capacity and highest release of C by desorption and as CO_2. The clays of the three soils differed in mineralogy, surface area and CEC, but these differences cannot explain the higher sorption capacity of the two added clays compared to the native clay from the loamy sand. We hypothesise that the higher organic C and lower Fe/Al content of the native clay reduced its capacity to sorb the added WEOC and increased desorption and C availability to microbes.

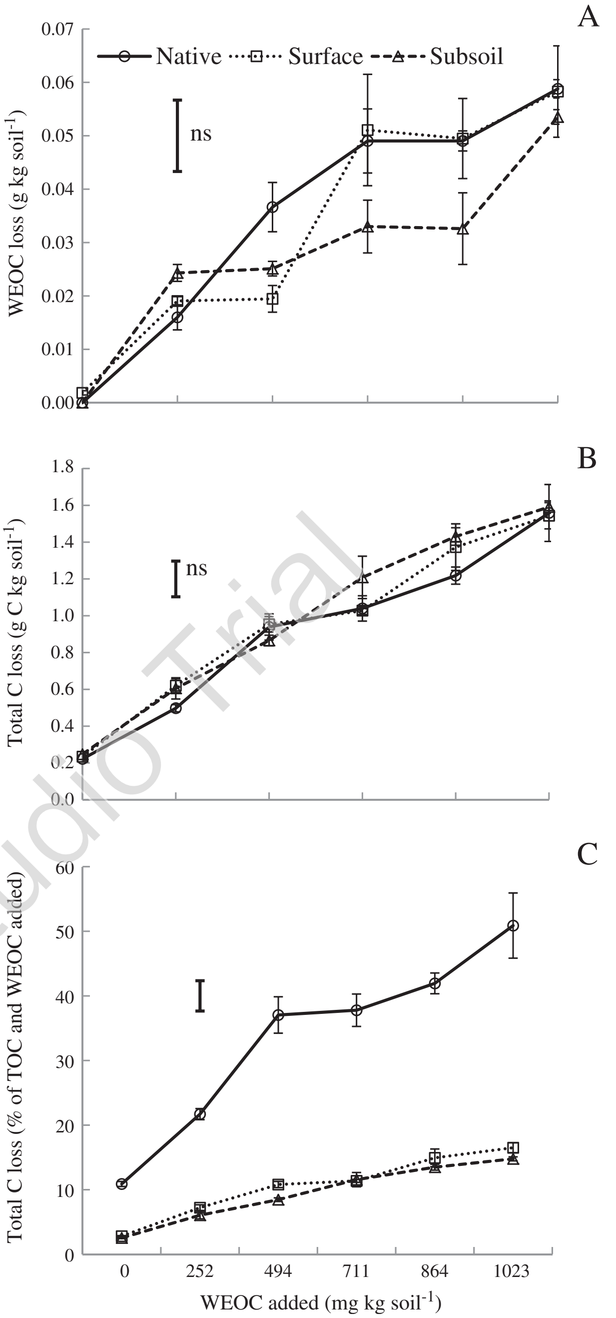

Fig. 3. WEOC in the leachate ($WEOC_{loss}$) at the end of the experiment after addition of 0–1023 mg WEOC from compost extract per kg soil to the loamy sand alone (native) or mixed with clay isolated from surface (surface) or subsoil (subsoil) after leaching with reverse osmosis water at the end of experiment (A) and total C loss ($WEOC_{leachate}$ + Respiration + $WEOC_{loss}$) in mg kg^{-1} soil (B) or in percentage of TOC + C added (C). Single vertical lines indicate least significant difference (clay treatment × WEOC concentration); n = 3 ± standard error, ns is non-significant.

In soils, DOC sorption has been shown to be positively related to clay content (Benke et al., 1999; Nelson et al., 1997). Thus, the lower clay content of the loamy sand alone compared to the loamy sand amended with the clay isolated from surface or subsoil may explain its lower sorption capacity. However, the lower sorption of the clay in the loamy sand was also evident when expressed per g clay in the WEOC

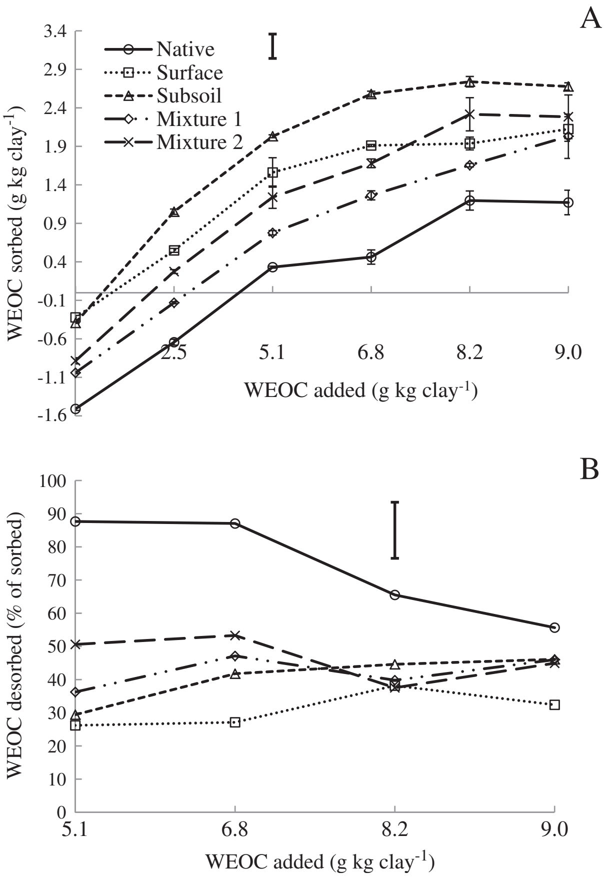

Fig. 4. WEOC sorption in mg C kg clay^{-1} (A) and desorption in percentage of C sorbed (B) after addition of 5.1–9.0 g WEOC from compost per kg clay by the clay fraction isolated from the loamy sand (native), surface (surface) or subsoil (subsoil) and mixtures of native + surface clay (mixture 1) and native plus subsoil clay (mixture 2). Single vertical lines indicate least significant difference (clay treatment × WEOC concentration); n = 3 ± standard error.

leaching experiment and in the sorption and desorption experiment with the isolated clays. Therefore, the differences in C sorption and loss among the soils are related to the properties of the clays.

Previous studies showed that illite has a lower DOC sorption capacity than smectite and kaolinite (Nelson et al., 1997; Ransom et al., 1998). Therefore the lower sorption capacity of the native clay from the loamy sand could be related to its high illite content. However, the smectite content of the other two clays was low (<10%) which suggests that their higher sorption capacity is not related to smectite content. Moreover, the surface and subsoil clays differed in illite and kaolinite content, but had similar effects on WEOC sorption, desorption and cumulative respiration. This suggests that clay mineralogy is not an important factor for C sorption in the soils used here.

Surface area is positively related to DOC and OC sorption (Kaiser et al., 1996; Nelson et al., 1993). However in this study, the native clay had the highest surface area and although the subsoil and surface clays differed in surface area, they did not differ in WEOC sorption and desorption or their effect on respiration. Thus, differences in surface area cannot explain the results of this study.

Organic matter and clays are negatively charged. Therefore divalent cations such as Ca^{2+} on the exchange sites play an important role as bridges between organic matter and clays (Setia et al., 2013; Whittinghill and Hobbie, 2012). Cation exchange capacity and the concentration of exchangeable Ca^{2+} were higher in the native clay from the loamy sand than in the other two clays. This should have led to greater WEOC sorption and retention by the native clay which was not the case in either the leaching or the sorption/desorption experiment.

Fe and Al oxides bind DOC more strongly than clay minerals (Kaiser and Zech, 2000) and DOC sorption was higher in clays covered with Fe and/or Al oxides (Jardine et al., 1989; Kaiser et al., 1996). Although we only measured water-extractable Fe and Al concentrations in our clays, we can assume that the observed differences are due to different concentrations of amorphous Fe and Al oxides in the isolated clays because according to Darke and Walbridge (2000), exposed amorphous Fe and Al oxides are the main contributors to the Fe and Al concentrations in water extract of soils. Therefore, the lower water extractable Fe and Al concentrations of the native clay can explain its lower C sorption compared to the surface and subsoil clays (Table 1). The surface and subsoil clays differed in water soluble Fe and Al concentrations, but they had similar effects on WEOC sorption, desorption and cumulative respiration in the present study. This suggests that other clay properties also play a role in C sorption and desorption in this study.

High TOC content of soils or clays can reduce sorption of added DOC by coating the surfaces (Jardine et al., 1989; Kaiser et al., 1996). According to Keil et al. (1994), surface loadings of 50–110 μg organic C m^{-2} would be expected if the surface of minerals is coated by a monolayer of organic C. Based on native TOC contents and surface area of the clays, it can be calculated that the native clay had an organic C surface loading of 97 μg C m^{-2} which is close to the maximum given by Keil et al. (1994). The organic C surface loading of the clays from the surface and subsurface on the other hand is 24–38 μg C m^{-2}, thus below the values from Keil et al. (1994). Thus it appears that the high TOC content of the native clay is another factor contributing to the lower WEOC sorption and the higher desorption and respiration compared to the other two clays.

5. Conclusion

Differences in clay mineralogy, surface area and cation exchange capacity cannot explain the lower WEOC sorption capacity of the clay from the loamy sand compared to that from the other two soils. Based on the results of this study, we hypothesise that the explanation of the low sorption capacity of the native clay is its high TOC content and low Fe/Al concentrations which prevented sorption of the added WEOC. It should be noted that only three soils/clays were used in this study. To confirm or reject the importance of TOC content and Fe/Al concentrations or other clay properties for WEOC sorption and release experiments with more clay soils should be conducted.

Conflicts of interest

There are no actual or potential conflicts of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

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CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

Composting of garden and urban food waste is a valuable alternative to landfills or incineration. Further, compost can partially replace inorganic fertiliser or be used together with inorganic fertiliser because it can provide organic matter and supply nutrients and thereby improve soil physical, chemical and biological properties (Paradelo *et al.*, 2007; Chamini *et al.*, 2008). Compared to other organic amendments, compost has a slower decomposition rate and is free of pathogens (Bernal *et al.*, 2009). The slow decomposition rate enables longer lasting effect of compost for plant growth and development.

The benefit of compost for agriculture and horticulture is well-known. Compost application can increase soil organic matter content (Celik *et al.*, 2004; Korboulewsky *et al.*, 2004; Weber *et al.*, 2007; Hargreaves *et al.*, 2008; Lakhdar *et al.*, 2009) and improve soil physical properties such as structural stability (Tejada *et al.*, 2009), aggregate formation (Celik *et al.*, 2004; Sodhi *et al.*, 2009), hydraulic conductivity (Curtis and Claassen, 2009) and soil water holding capacity (Aggelides and Londra, 2000; Curtis and Claassen, 2005). Compost application also affects chemical and biological soil properties and provides nutrients for plants (Hargreaves *et al.*, 2008; Lakhdar *et al.*, 2009). However, little is known about the effect of compost on plant available water under water-limiting conditions.

However, compost can also be a threat to the environment because compost amendment can increase nutrient leaching, e.g. NO_3^-N (Mamo *et al.*, 1999) and dissolved organic matter (Borken *et al.*, 2004; Wright *et al.*, 2010). The dissolved organic matter from compost can be lost via leaching or runoff into water bodies and ground water (Baldock and Skjemstad, 2000; Beesley and Dickinson, 2010) which can have detrimental effects on water quality and impact adjacent terrestrial systems (Jacinthe *et al.*, 2004; Evans *et al.*, 2005) which can be exacerbated by increased mobility of harmful metals (Beesley and Dickinson, 2010). Clay addition to compost or the under-lying soil may reduce nutrient loss from compost because of the capacity of clay for sorption of organic matter. Clay-sized particles can bind organic matter via cations and oxides covering the clay surface which not only reduces leaching but also makes the organic matter less accessible to soil microbes (Amato and Ladd, 1992; Nelson *et al.*, 1997).

In this thesis the effect of compost on soil water content and nutrient availability under water limiting condition was studied. In addition, this study assessed the effect of clay addition to compost or soil on nutrient availability and leaching.

In pot, field and incubation experiments, the following aims were addressed: (1) to assess the effect of compost on soil water content and plant growth under both well-watered and drought stressed conditions, (2) to evaluate the long term effect of mulched compost after a single application, (3) to compare the effects of mulched and incorporated compost on water and nutrient uptake and plant growth in the field, and (4) to determine the effect of clay addition to compost or sandy soil on nutrient availability and leaching.

7.1. Conclusions

The pot experiments described in Chapters 2 and 3 showed that compost application increased plant growth, especially root mass and length. In the first study, tomato was grown in a sandy soil without compost or with either incorporated or mulched compost. Compost addition increased tomato shoot and root growth under well-watered and drought stressed conditions with a greater effect by incorporated compost (Chapter 2). Furthermore, mulched compost addition once three years previously increased root mass and length of pepper plants under well watered and drought stressed conditions (Chapter 3). Compared to the un-amended control, both incorporated and mulched compost increased tomato shoot N and K concentrations in the drought stressed plants, but not in the well watered plants (Chapter 2). In addition, compost applied as mulch once three years previously increased soil organic C and

N concentrations (Chapter 3). These results show that an important aspect of compost application is the increased root growth which can be due to increased plant growth and soil structural stability. The greater root growth improves nutrient uptake and recovery after drought. These findings are novel because the effect of compost on plant growth under drying and rewetting cycles has not been studied before under controlled conditions.

Compost addition increased soil water content at both field capacity and permanent wilting point, but only incorporated compost increased total available water to tomato plants (Chapter 2). Even the single compost application three years previously increased total available water and water availability to capsicum in well-watered, but not in drought stress conditions (Chapter 3).

Mulched compost did not influence gas exchange and had no effect on water use efficiency and recovery capacity of tomato and capsicum after drought (Chapters 2 and 3). For the first time these chapters show that incorporated compost increased the speed of recovery of gas exchange after drought which can be explained by the stimulation of root growth (Chapter 2).

In the field experiment with vines (Chapter 4), the plants were irrigated regularly therefore they did not experience long-term drought stress but the top soil where the majority of active roots are located, dried out between irrigation events. Mulched compost increased the soil water content at 10 cm depth but not in the deeper layers. This higher water content in the topsoil may have allowed greater nutrient uptake between irrigation events and thereby contributed the positive effects of compost on vine growth such as increased leaf area index, rate of photosynthesis per plant at flowering, pea size and maturity, leaf N and P concentrations, yield and specific berry weight and reduced the number of chlorotic leaves at harvest with no adverse effect on berry quality.

Two incubation and leaching experiments were carried out to assess the effect of clay addition to compost or sandy soil on nutrient leaching. In the first experiment, sandy soil was non-amended or amended with compost alone at a rate 27.3 g kg^{-1} or with a mixture of compost and 5% or 20% (w/w) of a fine-textured soil(Chapter 5). Compost increased nutrient availability and leaching compared to the non-amended control. Addition of fine-textured soil to compost reduced cumulative respiration and N and P leaching and the effect was more pronounced at 20%. This study showed that the addition of fine-textured soil to compost can reduce N and P leaching which could enhance and prolong the positive effects of compost on soil fertility. In the second incubation experiment, two clays isolated from a surface soil and subsoil were added to a loamy sand (98.1 g kg^{-1}) and these substrates were leached with different concentrations of water-extractable organic C from compost (Chapter 6). Clay addition reduced C loss (mg C per kg soil) via leaching and respiration by increasing the sorption capacity. Clay properties such as mineralogy, surface area, cation exchange capacity and exchangeable Ca concentration did not explain the differences between clay types in C sorption and loss. However, C sorption capacity was greater in clays with low indigenous organic C and high Fe/Al concentrations. From these two incubation experiments it can be concluded that clay addition to compost or soil can in reduce the risk of entrophication and increase C sequestration by reducing C loss via leaching and respiration if the added clays have low total organic C and high Fe/Al concentrations.

7.2. Recommendations for future research

This research provided useful information for producers and users of compost. Compost not only provides nutrients for plant growth and development, but also has beneficial effects on plant growth under drought conditions by increasing root mass and length which allows greater water uptake. Clay addition to compost or sandy soil can reduce nutrient leaching from compost which can prolong the effect of compost particularly clays with low total organic C and high Fe/Al concentrations. However, the research also generated a number of questions which could be addressed in future to optimize the use of compost and clay for agriculture and horticulture.

1. In this research, only a few different types of compost were used. However it is well-known that compost effects on soil properties vary with particle size and nutrient content. Therefore it would be important to conduct similar experiments with composts of different particle sizes and nutrient content.
2. The field experiment was conducted only within the first year after compost application under well watered conditions. To better evaluate the effect of compost, the longer term effect of compost application on soil water availability and plant growth under water limiting condition should be determined.
3. The incubation experiments showed that clay addition to compost or sandy soil can reduce nutrient leaching and increase C sequestration. This would need to be verified under field conditions over a longer period of time.
4. The second incubation experiment suggested that certain clay properties are particularly important for organic C retention. This would need to be verified by using a greater number of clay soils that vary in properties such as organic C content, mineralogy, surface area, cation exchange capacity and Fe/Al concentration. Having identified the most effective clay soils, different rates of clay addition could be used to determine the optimal addition rate. This could be followed by longer term field experiments.
5. In the experiments with plants, only compost was used. However the incubation experiments showed that clay addition to compost can affect nutrient availability and leaching and may also influence water retention and availability. This could be addressed in experiments with plants amended compost with or without clay under well-watered and drought conditions.

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