Nutr Cycl Agroecosyst (2018) 111:155–173
https://doi.org/10.1007/s10705-018-9931-9

ORIGINAL ARTICLE

Agronomic and economic benefits of green-waste compost for peri-urban vegetable production: implications for food security

Simon M. Eldridge · **Kwong Yin Chan** · **Nerida J. Donovan** · **Fadi Saleh** · **Leanne Orr** · **Idris Barchia**

Received: 3 September 2017 / Accepted: 15 June 2018 / Published online: 25 June 2018

Abstract A long-term field experiment in western Sydney evaluated the effect of source-separated green-waste (garden organics) compost on peri-urban vegetable crop yields and economic returns, compared to farmer practice. Comparisons were made over 10 vegetable crops between a compost (COMP) treatment (one off application of 125 dry t ha^{-1} of green waste compost at the start and then every five crops, supplemented with urea when required), a mixed (MIX) treatment (one-off compost application of 62.5 dry t ha^{-1} at start and then every five crops, but with inorganic NPK fertiliser inputs for each crop) and a conventional farmer practice (FP). Both COMP and MIX treatments consistently achieved similar or higher yields than FP, but the yield gains were more pronounced for COMP. COMP and MIX treatments delivered benefit–cost ratios of 3.3 and 2.6 respectively compared to FP over the 10 crops, indicating that this system could deliver economic benefits to growers as well as improve soil quality and the environment. Follow up large applications of compost generated more substantial yield increases in responsive vegetable crops and economic benefits. The substantial capsicum crop yield response provided a classic example of closing a crops 'yield gap' through improvements to soil quality with organic inputs, with implications for food security. The COMP treatment

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Kwong Yin Chan formerly at New South Wales Department of Primary Industries, Richmond, NSW, Australia.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10705-018-9931-9) contains supplementary material, which is available to authorized users.

S. M. Eldridge
Wollongbar Primary Industries Institute, New South Wales Department of Primary Industries, Wollongbar, NSW 2477, Australia

S. M. Eldridge (✉)
School of Agriculture and Food, Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Parkville, VIC 3010, Australia
e-mail: simon.eldridge@unimelb.edu.au

K. Yin Chan
New South Wales Department of Primary Industries, Richmond, NSW 2753, Australia

N. J. Donovan · F. Saleh · I. Barchia
Elizabeth Macarthur Agricultural Institute, New South Wales Department of Primary Industries, Menangle, NSW 2568, Australia

L. Orr
Leanne Orr Economics Consulting, Berry, NSW 2535, Australia

lifted the capsicum yield to ~ 60 t ha^{-1}, 50% above its perceived maximum potential crop yield for Eastern Australia. The value of larger applications of compost for soil quality, fertiliser savings, crop yield and farm income was apparent.

Keywords Soil quality · Recycled organic waste · Benefit–cost analysis · Yield gap

Introduction

There is often a significant difference between current yields and potential maximum yields for any given crop in our agricultural systems, and reducing these 'yield gaps' is seen as a key strategy for improving global food security (Lobell et al. 2009; Pradhan et al. 2015). Lal (2004, 2010) argues that improving soil quality by increasing soil organic carbon (C) levels may be very important for optimising crop yields and improving food security.

Studies have found that agricultural systems with high organic inputs often have improved soil microbial activity and function (Reeve et al. 2010; Kremer and Hezel 2013). The application of green-waste composts have also been associated with reductions in greenhouse gas emissions (Dalal et al. 2009, 2010; Vaughan et al. 2011), the supression of some soil-borne pathogens for vegetables and other crops (Termorshuizen et al. 2006; Pane et al. 2013; Suárez-Estrella et al. 2013), and a general improvement in soil quality relative to conventional practice (Wells et al. 2000). However, earlier research by Cook et al. (1998) indicated that large applications of garden organics compost in the order of 150 t ha^{-1} were required to increase the yield of some cereal crops, such as spring barley.

Worldwide, vegetable production is often located in peri-urban areas close to large cities. Peri-urban vegetable production supplies much of the vegetables (~ 20% total food; > 50% Asian vegetables, tomatoes, spring onions etc.) consumed by Sydney's 4 million inhabitants. A paired site survey of vegetable farms in the Sydney region (Chan et al. 2007a) found that these soils were depleted of soil organic carbon (C), with losses of 43% of organic C on average, and soils had accumulated very high levels of bicarbonate extractable phosphorus (P) (~ 300 mg kg^{-1}) from excessive fertiliser inputs. Thus, it was apparent that there was a need for alternative management practices to improve the sustainability of intensive vegetable production in this peri-urban area. Around 2004, government legislation and strategies facilitated the successful diversion of source-separated garden organics (i.e. household garden prunings and grass clippings) from landfill to composted garden organics (cGO). Large quantities of cGO (i.e. ~ 0.3 million t $year^{-1}$) were being generated in the Sydney basin, and this was projected to increase (Chan et al. 2007b, 2008). Around 90% of the recycled organics produced was used in the urban amenity market segment (i.e. landscaping and domestic gardens), and this market segment was thought to be close to saturation (DEC 2004). In contrast, only a very small proportion (i.e. ~ 4%) of the cGO generated was being used in agriculture, and it was therefore thought that there was great potential for its use in intensive vegetable production in the peri-urban areas around the Sydney Basin. It was on this basis that the long term compost vegetable field experiment was established at Camden, South-western Sydney in 2005.

Farmers are hesitant to substitute chemical fertilisers with compost because the agronomic and economic value of compost have not been well quantified, particularly for non-nutrient factors (Evanylo and Sherony 2002). Because the benefits of compost can last more than one season and some of the benefits may take several years to manifest (ROU 2006), the benefits need to be quantified and verified in the field under local conditions over several successive crops through scientifically valid benefit–cost studies.

Our field experiment over 10 consecutive vegetable crops in a peri-urban setting aimed to test the following hypotheses;

1. A green waste compost based vegetable production system (with an agronomic N based compost loading for the first crop and supplemented with inorganic N when required) can achieve better crop yields than farmer best practice (based on inorganic NPK fertiliser and chicken manure inputs).
2. A compost based peri-urban vegetable production system (as described in this study) can deliver

higher farm income for farmers than current farmer best practice.

3. A repeat of the 5 crop compost system (with a further one-off large application of compost followed by 5 crops) will produce even more pronounced vegetable crop yield and farm income benefits compared to farmer best practice, than that observed in the first 5 crops of this system due to the further improvements to soil quality associated with the increased soil organic carbon levels.

An earlier benefit–cost analysis (BCA) that was carried out on the first five crops of the field experiment concluded that the compost treatment paid for itself compared to farmer practice (with a benefit–cost ratio of 1), but with additional unvalued environmental benefits (Chan et al. 2011). In this paper, we present the agronomic yield and benefit–cost analysis results for the compost-based production systems compared to conventional farmer practice over a long-term sequence of 10 consecutive vegetable crops, representative of peri-urban agriculture in South-western Sydney.

Materials and methods

Site and soil characteristics

The field trial was located at the NSW Department of Primary Industries (DPI) 'Centre for Recycled Organics in Agriculture' near Camden (70 m Australian Height Datum at 150°42′32″E, 34°05′45.6″S) in South western Sydney, New South Wales, Australia. The site had a long history of intensive cropping and forage production prior to the field experiment. The soil at the site is a Chromosol/Dermosol inter-grade (Isbell 1996) or Lixisol (FAO 2006), with a topsoil that is hard setting with low organic carbon. The site topsoil properties are described in detail in Chan et al. (2008, 2010) and the important properties are presented in Table 1. The methods of Rayment and Higgins (1992) were used to determine soil pH_{CaCl2}, and EC of a 1:5 soil: water suspension [methods 3A1 and 4B1], total C and N by Dumas dry combustion [methods 6B3], Mineral N (NO_3^-–N and NH_4^+–N) from a 1:5 extraction with 2 M KCl [method 7C2] and Colwell P [method 9B2]. Total (acid extractable) phosphorus (P) content was determined by acid extraction [method 8—microwave digestion, SPAC 1998] prior to analysis by ICP-AES [USEPA 6010]. The exchangeable cations were determined following the compulsive exchange method of Gillman and Sumpter (1986) as documented [i.e. method 15E] in Rayment and Higginson (1992).

Treatments and experimental design

The field trial consisted of seven treatments in a randomised complete block design with 4 replicates of each treatment. The seven treatments are briefly outlined in Table 2. Individual plots were 5 m by 6 m with a 1 m buffer between plots. All plots were rotary hoed to a depth of 0.10 m to incorporate added amendments prior to forming the plot areas into three beds, each 1.2 m wide × 6.0 m long × 0.15 m high.

High and low initial levels of soil extractable P were included as factors in the experimental design in order to assess the impacts of high soil P levels (typical of Sydney basin vegetable farms) on vegetable crop yields (Chan et al. 2007a). For the high P treatments (T1, T2 and T3), triple superphosphate was applied to each plot at the start of the experiment (in 2005) at a rate equivalent to 680 kg P ha^{-1} and incorporated to 0.10 m, to raise the soil extractable P concentrations to levels similar to those observed in vegetable farm soils (~ 250 mg kg^{-1} in 0.10 m, Chan et al. 2007a). The site soil had a low concentration of bicarbonate extractable P (29 mg kg^{-1}) and this ensured the other treatments (T4, T5, T6, T7) were representative of new vegetable farms with no prior history of high fertiliser inputs.

The compost used in this field experiment was derived from source separated garden organics blended with 10% poultry manure (from laying chickens) and composted according to the Australian Standard AS 4454-2003 by a local commercial supplier. The properties of the composts and poultry manure used in this experiment are presented in Table 1. The compost was applied as a single application at the beginning of the trial in 2005 at a rate of 125 dry t ha^{-1} for the full compost (COMP) treatments (T2, T5) and 62.5 dry t ha^{-1} in the mixed (MIX) treatments (T3, T6), and incorporated into the soil to a depth of 15 cm. A repeat of these compost applications were applied in 2008 prior to crop 6. The compost was applied and promptly incorporated into

Table 1 Properties of the soil (T = 0), poultry manure and compost used in the field trial

Treatment	pH^{a}_{Ca}	EC^{b}	TOC	TN	C/N	NH_4–N	NO_3–N	Colwell P	Exchangeable cations $[cmol (+) kg^{-1}]$			
		dS m^{-1}	g 100 g^{-1}	g 100 g^{-1}		mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	Na	K	Ca	Mg
Field trial soil (0–10 cm)	5.2	0.13	1.1	0.11	10	2	50	29	0.12	0.29	5.35	1.25

	pHw^{a}	EC^{b}	TOC	TN	C/N	NH_4–N	NO_3–N	Colwell P	TP	N:P ratio
		dS m^{-1}	g 100 g^{-1}	g 100 g^{-1}		mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	g 100 g^{-1}	
Compost no. 1 (crop 1)	5.6	3.14	21	1.1	19.1			1200	0.38	2.9
Poultry manure (crops 1–10)	8.1	9.20	32	3.1	10.3	6900	35	7500	2.60	1.2
Compost no. 2 (crop 6)	6.9	5.3	30	1.6	18.8	845	19	2200	0.72	2.2

TOC total organic carbon, *TN* total N, *TP* total P

[a] pH in 1:5 soil/0.01 M $CaCl_2$

[b] Electrical conductivity and pHw in 1:5 soil:water extract

Table 2 The field experiment treatments

Treatment	Soil P status[a]	Treatment description
T1—high P—farmer practice	High	Conventional farmer practice (half NPK as inorganic chemical fertiliser and half NPK as poultry manure)
T2—high P—full compost	High	One off application of compost at 125 dry t ha^{-1} prior to first crop with supplementary N as urea at ≤ farmer practice urea rate if required for 5 crops following compost application.
T3—high P—mixed	High	One off application of compost at half the full compost treatment rate and half NPK as inorganic chemical fertiliser
T4–low P—farmer practice	Low	As for T1, but with low initial soil P status
T5—low P—full compost	Low	As for T2, but with low initial soil P status
T6—low P—mixed	Low	As for T3, but with low initial soil P status
T7—low P—nil control	Low	Nil inputs, with low initial soil P status

[a] High soil P status—soil adjusted to bicarbonate extractable soil P status similar to high levels typical of vegetable farms of Sydney area (~ 250 mg kg^{-1}) at start of experiment; low soil P status—soil left with its inherent low concentration of bicarbonate extractable P (29 mg kg^{-1}) at the start of the experiment

the soil of the relevant treatment plots 4 weeks prior to the planting of crops 1 and 6 (refer to Table 3 for planting dates). The full compost rate for treatments T2 and T5 was determined to be 125 dry t ha^{-1} based on the recommended agronomic rate for N for the first crop (broccoli) and the total N content of the compost, assuming an availability index of 0.10 (i.e. 10% of compost total N is available to the crop) from Evanylo and Sherony (2002). The half compost rate for treatments T3 and T6 was thus 62.5 dry t ha^{-1}.

Before the planting of each crop, poultry manure was applied to the farmer practice (FP) treatment plots (T1, T4) and triple superphosphate was applied to both the FP treatment (T1, T4) and the MIX treatment (T3, T6) plots. Both amendments were incorporated to a soil depth of 15 cm. The poultry manure and triple superphosphate were applied to the appropriate treatment plots and incorporated into the soil 4 weeks prior to the planting of each crop (refer to Table 3 for crop planting dates). Potassium (K) as Muriate of Potash

Table 3 Cropping sequence and 'In-crop' rainfall (mm) and irrigation water applied for the ten vegetable crops in the field experiment

Crop	Season	In-crop rain (mm)	Irrigation (mm)	Irrigation (ML ha^{-1})
1. Broccoli *Brassica oleracea* var. *italica* L. 'Bellstar'	April 05–Aug 05	124	510	5.1
2. Eggplant *Solanum melongena* L. 'Black bell'	Dec 05–Mar 06	171	780	7.8
3. Cabbage *Brassica oleracea* L. var. *capitata* L 'Red Rookie'	May 06–Aug 06	193	450	4.5
4. Capsicum *Capsicum annuum* var. *annuum* L. 'Warlock'	Dec 06–April 07	443	447	4.5
5. Leek *Allium porrum* L. 'Admiral'	Jul 07–Oct 07	370	312	3.1
6. Capsicum *Capsicum annuum'* var. *annuum* L. 'Warlock'	Oct 08–Mar 09	230	436	4.36
7. Broccoli *Brassica oleracea* var. *italica* L. 'Prophet'	June 09–Oct 09	150	117	1.17
8. Lettuce *Lactuca sativa* var. *capitata* L. 'Univert'	Feb 10–April 10	227	96	0.96
9. Cabbage *Brassica oleracea* L. 'Kameron'	July 10–Nov 10	322	230	2.3
10. Sweet corn *Zea mays* L. 'SW108'	Feb 11–May 11	161	430	4.3

and N as urea were applied to four treatments (T1, T3, T4, and T6) for each crop as split side dressing surface applications by hand, without incorporation. The half-compost (i.e. MIX) treatments (T3 and T6) received half their NPK for each crop as inorganic fertilisers, identical to that for the FP treatments (T1 and T4).

The nutrient requirements of each crop were based on industry expert recommendations for agronomic rates of NPK fertiliser (Agfact/Primefact series 2016 and district horticulturalist advice). For the FP treatments (T1 and T4) half of the required N was applied as the inorganic fertiliser Urea (split surface applications over crop life) and the other half as poultry manure (incorporated into the soil prior to planting). The amount of poultry manure required was calculated from its total nitrogen content assuming an availability index of 0.60 (i.e. 60% of poultry manure total N is available to the crop) from Evanylo and Sherony (2002). For the FP treatment P and K fertiliser rates it was assumed that half of the crop requirement for P and K was also supplied by the poultry manure rate determined by the total N calculation, and so only half of the recommended agronomic rate of P and K were applied as inorganic fertiliser for this treatment, on this basis. The same amount of P fertiliser was applied to both the low and high P versions of each treatment throughout the experiment in order to determine the impact of background soil extractable P levels on crop yield. The P fertiliser application rates adhered to the recommended rate for the district for the whole experiment, so as to allow the option of studying the rate of build up of soil extractable P levels in these systems when adhering strictly to recommended practice compared to the alternative compost based systems.

For the COMP treatments (T2 and T5), plant sap tests for N were carried out on the sap from the petioles of each crop to monitor N nutrition in comparison to FP treatments (T1 and T4). This was done to inform if supplementary applications of urea were required or not for the COMP treatment (T2 and T5) plot soils. The inorganic chemical and organic fertiliser inputs for each treatment for all 10 vegetable crops are presented in Table 4.

Crops were managed following recommendations from the NSW Department of Primary Industries (Agfact/Primefact Series 2016) and industry handbook (Salvestrin 1998). The 10 vegetable crops grown in this experiment are presented in Table 3. After the harvesting of each crop, all of the non-harvestable crop residues on each plot were incorporated into the soil by rotary hoeing. Further details on the field experiment are provided in Chan et al. (2008, 2010). Drip irrigation was used to supply the crops with water and irrigation scheduling was based on data from 'Gbug®' (gypsum block) soil moisture sensors installed in all the treatment plots in two of the experimental blocks. Irrigation was applied when soil water potential at 20 cm depth was < -30 kPa. Total irrigation and rainfall for all crops is presented in Table 3.

Marketable crop yield data

Marketable yield estimates were obtained from the harvesting of the centre bed of each plot. Fresh weights were determined and expressed on a t ha^{-1} basis. Additional market measurements, such as number of lettuce per standard market box, number of corn per market box and number of boxes, were also recorded where required for pricing for the economic analysis.

Soil sampling and analysis

Soil samples were collected within 1 week following the transplanting of each crop by collecting 7 soil cores (0.05 m diameter, 0.15 m depth) from across the 3 beds within each plot and bulking the sample together to form a composite sample that was then split into subsamples for chemical, physical and biological analysis. The fresh soil sample for biological analysis was passed through a 2 mm sieve and all observable plant, root and fauna materials removed prior to storage at 4 °C until analysis. The other soil subsamples were air dried at 36 °C to a constant mass. The air dried soil sample for chemical analysis was then crushed to < 2 mm and passed through a 2 mm sieve for chemical analysis.

Table 4 Organic and inorganic fertiliser inputs for the individual vegetable crops under different treatments for the field experiment

Crop	1. Broccoli			2. Eggplant			3. Cabbage			4. Capsicum			5. Leek		
Treatment	COMP	MIX	FP	COMP	MIX	FP	COMP	MIX	FP	COMP	MIX	FP	COMP	MIX	FP
Fertiliser															
CGO (t ha^{-1})	125	62.5	0	0	0	0	0	0	0	0	0	0	0	0	0
PM (t ha^{-1})	0	0	4.03	0	0	3.24	0	0	4.3	0	0	3.25	0	0	3.62
U (kg ha^{-1})	0	163	163	0	130	130	133	200	200	200	266	266	425	425	425
TP (kg ha^{-1})	0	143	143	0	200	200	0	190	190	0	119	119	0	72	72
K (kg ha^{-1})	0	0	0	0	47	47	0	57	57	0	43	43	0	0	58
Dol (t ha^{-1})	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop	6. Capsicum			7. Broccoli			8. Lettuce			9. Cabbage			10. Sweet Corn		
Treatment	COMP	MIX	FP	COMP	MIX	FP	COMP	MIX	FP	COMP	MIX	FP	COMP	MIX	FP
Fertiliser															
CGO (t ha^{-1})	125	62.5	0	0	0	0	0	0	0	0	0	0	0	0	0
PM (t ha^{-1})	0	0	2.69	0	0	3.31	0	0	3.26	0	0	3.29	0	0	4.39
U (kg ha^{-1})	0	67	267	0	67	163	0	77	77	163	163	163	217	217	217
TP (kg ha^{-1})	0	143	143	0	143	143	0	143	143	0	199	199	0	73	73
K (kg ha^{-1})	0	67	67	0	0	0	0	0	0	0	57	57	0	115	115
Dol (t ha^{-1})	0	0	0	0	0	0	0	0	0	0	0	0	0	2.16	3.00

CGO garden organics compost, *PM* poultry manure, *U* urea, *TP* triple super phosphate (Triphos), *K* Muriate of Potash (KCl), *Dol* dolomite, *COMP* compost treatments (T2 and T5), *MIX* mixed treatments (T3 and T6), *FP* farmer practice treatment (T1 and T4)

The soil properties discussed in relation to the influence of soil quality changes on crop yield responses for crops 4 and 6 are soil total organic carbon, microbial biomass, effective cation exchange capacity (eCEC) and Colwell P. Microbial biomass C was determined in triplicate on 20 g samples of moist soil according to the chloroform fumigation extraction method of Vance et al. (1987). The total dissolved organic C content of the 80 mL 0.5 M K_2SO_4 extraction solutions for the fumigated and unfumigated soil samples were determined using a Shimadzu TOC analyser (Wu et al. 1990), with the soil microbial biomass C calculated as the difference between fumigated and unfumigated soil samples multiplied by a conversion factor of 2.64 (Wu et al. 1990). The effective cation exchange capacity (eCEC) of the air dry < 2 mm soil samples were determined according to the compulsive exchange method of Gillman and Sumpter (1986) as documented in Rayment and Higginson (1992), whilst the Colwell P and total organic C levels were also determined by the methods of Rayment and Higginson (1992) as outlined in "Site and soil characteristics".

Statistical analyses of marketable crop yield and soil data

The vegetable yield and soil data for the different treatments were analysed using analysis of variance. Data were fitted with a linear mixed model accounting for initial soil P status (high and low P), input treatments (i.e. compost, mix, farmer practice, control) and their interactions, experimental error and block effects. The data were analysed using a residual maximum likelihood (REML) estimation, and the treatment means compared using the Fisher's *F*-protected least significant difference (LSD) value at the 5% significance level.

Economic analyses

Due to the intensive nature of the vegetable cropping system which involves the production of two or three crops each year and the fact that the impact from using compost extends for several years, development budgeting (Gittinger 1982) was used to account for the full impact of compost in the field trial. Enterprise budgets were developed for each of the vegetable crops for each of the treatments (COMP, MIX and FP) (see Appendix B, Supplementary material file). These budgets were informed by previous NSW DPI vegetable budgets (NSW Agriculture 2001) with yield, costs of compost, fertilisers and other production costs gathered from the field trial. As there was no significant ($P = 0.05$) yield difference between high P and low P, average yields were used for each of the three treatment groups (see Appendix A, Supplementary material file). All the costs were based on the expenses at the time they were incurred. All costs and benefits were converted to "real present value figures" using a GDP deflator with the base year being set to 2009/10 (= 100) for valid comparison.

Benefit–cost analysis (BCA) was chosen as the most appropriate economic method to assess each alternative farming practice compared to FP (conventional farmer practice base case).

The cost of the compost including transport and contract spreading are presented in Table 5. The compost was applied to the Compost treatment plots at a rate of 125 dry t ha^{-1} and half this rate (62.5 dry t ha^{-1}) for the mix treatment plots. The compost was incorporated into the soil using routine soil cultivation techniques in the crop bed-forming preparation.

Results

Crop yield response

The mean marketable yields achieved by each treatment for each of the 10 vegetable crops are presented in Table 6. The full compost (COMP) treatment matched or exceeded the yield for farmer practice (FP) treatment for all ten vegetable crops. Out of the first five vegetable crops grown following the initial compost applications for the COMP and MIX treatments in the experiment, no significant differences were found between the COMP and FP treatments for all crops except crop 4—capsicum (Table 6). For this crop, the yield of the low initial soil P (LP) version of the COMP treatment (T5) was 35% higher than the LP version of the FP treatment (T4) and 20% higher than the HP farmer practice treatment (T1) yield (i.e. 42.1 vs 31.0 and 35.0 t ha^{-1}). It is important to note that the COMP treatment capsicum crop yield value of 42.1 t ha^{-1} was slightly higher than the perceived maximum potential yield for the capsicum crop in

Table 5 Costs of using compost for the COMP and MIX treatments

COMPOST COST	Application no. 1 (prior to crop 1)		Application no. 2 (prior to crop 6)	
	COMP[a]	MIX	COMP	MIX
Cost ($\$$ m^{-3})	33.8	33.8	46.5	46.5
Bulk density (dry t m^{-3})	0.5	0.5	0.5	0.5
Cost ($\$$ dry t^{-1})	67.6	67.6	93.0	93.0
Compost rate dry (t ha^{-1})	125.0	62.5	125.0	62.5
Spreading – 44 kW tractor + 600 litre spreader ($\$$ ha^{-1})	4.5	4.5	4.5	4.5
Cost ($\$$ ha^{-1})	8455	4227	11,630	5815

[a] *COMP* compost treatments (T2 and T5), *MIX* mixed treatments (T3 and T6)

Table 6 Marketable yield (fresh weight in t ha^{-1}) of the ten successive vegetable crops under different treatments

Treatment	Input	Yield (fresh weight) t ha^{-1}									
		1. Broccoli	2. Eggplant	3. Cabbage	4. Capsicum	5. Leek	6. Capsicum	7. Broccoli	8. Lettuce	9. Cabbage	10. Sweet corn
T1 (HP)[a]	FP	8.7 **a**	70.8 **a**	14.6 **a**	35.0 **bc**	12.2 **a**	32.8 **c**	17.2 **a**	38.3 **cd**	55.4 **a**	22.2 **a**
T2 (HP)	COMP	8.7 **a**	75.8 **a**	14.5 **a**	38.4 **ab**	12.9 **a**	62.4 **a**	19.0 **a**	45.6 **ab**	57.4 **a**	25.6 **a**
T3 (HP)	MIX	8.6 **a**	70.4 **a**	11.7 **a**	29.8 **c**	10.0 **ab**	45.0 **bc**	18.8 **a**	41.5 **bcd**	52.9 **a**	22.8 **a**
T4 (LP)	FP	9.1 **a**	70.4 **a**	18.1 **a**	31.0 **c**	13.5 **a**	31.9 **c**	19.7 **a**	37.7 **d**	54.1 **a**	22.7 **a**
T5 (LP)	COMP	11.3 **a**	75.2 **a**	16.8 **a**	42.1 **a**	12.3 **a**	59.8 **a**	20.6 **a**	47.0 **a**	49.4 **a**	24.4 **a**
T6 (LP)	MIX	10.4 **a**	77.9 **a**	15.5 **a**	29.6 **c**	6.18 **b**	50.6 **ab**	19.4 **a**	41.9 **bcd**	58.9 **a**	25.3 **a**
T7 (control)	Nil	4.9 **b**	45.0 **b**	0.0 **b**	6.1 **d**	1.5 **c**	4.2 **d**	3.8 **b**	15.8 **e**	28.6 **b**	13. 8 **b**
LSD$_{5\%}$		3.8	14.5	7.7	6.4	4.3	13.6	4.7	4.8	14.9	4.0

A different lower case letter after each value within each column indicates a significant difference between those treatment means for that crop at $P = 0.05$ (from ANOVA using the Fisher F-protected LSD value at 5% significance). Least significant difference value for each crop at $P = 0.05$ (LSD$_{5\%}$) provided

[a] *HP* High P (i.e. initial high levels of plant available phosphorus in the soil), *LP* Low P (i.e. initial low levels of plant available phosphorus in the soil), *COMP* compost treatments (T2 and T5), *MIX* mixed treatments (T3 and T6), *FP* farmer practice treatment (T1 and T4)

south eastern Australia of 40 t ha^{-1} (Bartha 1983). For the most part, MIX treatments (T3 and T6) matched the comparable FP treatments (T1 and T4) for each of the first five crops following the initial compost applications of 62.5 dry t ha^{-1}. Apart from the LP MIX treatment (T6) low yield result for crop 5 (leek) which was an anomaly, no significant difference was found between the MIX treatment crop yields and those of the FP treatments for all of the first five vegetable crops (Table 6).

The yield results for the second set of five vegetable crops (crops 6–10) grown following the repeat compost application are also presented in Table 6. For the second set of five vegetable crops grown, the average yields of both the COMP treatments and the MIX treatments either matched or exceeded the yield for the FP treatment. No significant difference ($P < 0.05$) was found between the mean crop yields of the COMP, MIX, and FP treatments for crop 7 (broccoli), crop 9 (cabbage), and crop 10 (sweet corn) (see Table 6). However significant differences were found between the mean crop yields of the COMP and FP treatments for crops 6 (capsicum) and 8 (lettuce), which followed the second compost application (Table 6).

For crop 6 (capsicum) which was the first crop following the repeat application of compost, the COMP treatments (T2 and T5) achieved yields almost double that of the FP (T1 and T4) whilst the T6 MIX treatment (½ compost: ½ chemical) achieved a yield > 50% higher than the FP yield (Table 6). To put this in context, the FP mean yields for this crop of 32.8 and 31.9 t ha^{-1} are much higher than the average district yield of 12 t ha^{-1} (Beckingham and Seymour 1984) and only slightly less than the perceived potential maximum yield of 40 t ha^{-1} for capsicums (Bartha 1983). Both of the COMP treatments (T2, T5) were well above the maximum yield level with yields of 62.4 and 59.8 t ha^{-1} respectively (see Fig. 1). The MIX treatment (T6) also achieved a high mean yield with 50.6 t ha$^{-1,}$ which was significantly higher than the comparable FP treatment, and not significantly different to the COMP yield results. It is also apparent in Fig. 1 that the FP treatments (T1, T4) achieved similar yields for capsicum in crop 6 as they did in crop 4, whilst the crop 6 capsicum yields for the COMP and MIX treatments have improved significantly from their crop 4 capsicum yields. It is apparent in Fig. 1 that the first compost application significantly increased the yield for COMP treatment (T5) by around 30% compared to the FP treatment (T4) when grown as the 4th crop following application. This compares to a significant increase in capsicum yield for the COMP treatment (T5) of around 87% compared to FP (T4) when the crop was grown as the first crop (crop 6) following the second application of compost (Table 6; Fig. 1). The MIX treatments (T3, T6) yields were not significantly different to the FP treatments (T1, T4) for the crop 4 capsicum, but one of the MIX treatments (T6) was found to have achieved a 59% higher yield than farmer practice (T4) for the crop 6 (capsicum), following the second compost application (Table 6).

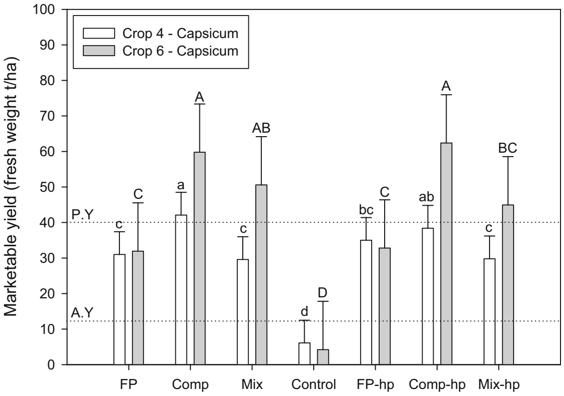

Fig. 1 Comparison of treatment marketable yields (fresh weight t ha^{-1}) within the two capsicum crops—Crop 4 (the fourth crop following the initial application of compost) and crop 6 (the first crop following the repeat application of compost). FP is farmers practice, Comp is Compost, Mix is Mixed, control is the control treatments. hp are treatments with initial soil P levels adjusted to high P status. Error bars represent LSD 5% values for each crop. Treatment columns with different lower case or different upper case letters have mean values that are significantly different at $P = 0.05$ (Determined by ANOVA using the Fisher F-protected LSD value at 5% significance) for each respective crop. The dotted lines labelled A.Y and P.Y represent the average local yield of 12 t ha^{-1} (Beckingham and Seymour 1984) and the crop potential yield of 40 t/ha (Bartha 1983) respectively, for Capsicum. FP = (T4); Comp = (T5); Mix = (T6); Control = (T7); FP-hp = (T1); Comp-hp = (T2); Mix-hp = (T3)

The higher capsicum crop yields (in fresh weight t ha^{-1}) in the COMP and MIX treatments following the second application of compost, appears to be due to a significant ($P < 0.05$) increase in the number of marketable fruit produced per plant (Table 7). The COMP and MIX treatments effectively increased the number of fruit per plant from around 4.6 for farmer practice up to 8.4 and 7.1 respectively, which is almost to the perceived potential limit for the crop of 10 marketable fruit per plant (Bartha 1983). The compost treatments thus helped the capsicum crop to achieve almost optimal production (Fig. 1).

The only other crop to achieve a significant yield benefit from the COMP treatment was crop 8 (lettuce), where the COMP treatment (T5) yield of 47 t ha^{-1} was 24.7% ($P < 0.05$) higher than the FP treatment (T4) yield of 37.7 t ha^{-1} (Table 6). No significant difference was found between the yields of the MIX and FP treatments for this crop.

Another important finding from this study evident in the yield data for the 10 vegetable crops grown in this experiment (Table 6) was that no yield benefit was obtained by elevating the soil extractable P levels to the high levels typical of vegetable farms in the Sydney Basin. This finding is demonstrated in the fact that no significant differences ($P < 0.05$) were found between the yields of the high soil P (HP) and low soil P (LP) versions within each of the COMP, MIX and FP

Table 7 Mean fruit production for crop 6—capsicum

Treatment	No. fruit/bed (24 plants)	No. fruit/plant	Proportion of maximum no. fruit/plant (%)[a]
T1 FP—HP[b]	116 **c**[*]	4.8	48
T2—COMP—HP	201 **a**	8.4	84
T3—MIX—HP	145 **bc**	6.0	60
T4—FP—LP	111 **c**	4.6	46
T5—COMP—LP	202 **a**	8.4	84
T6—MIX—LP	169 **ab**	7.1	71
T7—nil control—LP	21 **d**	0.9	9
LSD ($P = 0.05$)	44		
Probability (F)	< 0.001		

*Different letters indicate a significant difference between treatments at $P = 0.05$

[a] Based on a maximum of 10 fruit per capsicum plant (Bartha 1983)

[b] *HP* High P (i.e. initial high levels of plant available phosphorus in the soil), *LP* Low P (i.e. initial low levels of plant available phosphorus in the soil), *COMP* compost treatments (T2 and T5), *MIX* mixed treatments (T3 and T6), *FP* farmer practice treatment (T1 and T4)

treatments for each of the 10 crops within the experiment (see Table 6). The experimental yield data presented in Table 6 was used to derive the yield inputs for the economic analysis (see Table S2, Supplementary material file).

Soil quality and the capsicum yield response

The soil total organic carbon (TOC) levels at planting are presented in Table 8 for the two capsicum crops (crop 4 and 6) along with other TOC associated soil properties (eCECand MBC) for crop 6 to show differences between the treatments which may have contributed to yield differences. Table 8 reveals that there were significant differences between the mean crop 4 soil TOC levels for the COMP, FP and MIX treatments with 1.9, 1.4 and 1.6 g 100 g^{-1} of TOC respectively. This correlated with a 30% higher yield for the T5-COMP treatment compared to T4-FP, and no significant difference between the MIX and FP treatments (see Table 6). However for crop 6, where both the COMP and MIX treatments had substantially higher yields compared to FP, it can be seen that the COMP and MIX treatment soils had TOC levels of 3.0 and 2.3 g 100 g^{-1} respectively while FP had a similar level to what it had for crop 4 (i.e. 1.4 g 100 g^{-1}) and also achieved a similar yield to crop 4 as well (see Tables 6, 8). So it would seem that a soil TOC level above 2 g 100 g^{-1} is important for achieving a yield response in capsicum in this hard setting soil type.

It is also apparent that the increased soil TOC levels associated with the compost inputs for crop 6 have led to significantly higher soil cation exchange capacity (eCEC) with benefits for cation nutrient storage and cycling, as well as significantly higher microbial biomass C levels for the COMP treatment compared to FP. This associated increase in soil MBC is particularly important as it indicates an increase in the size of the soil microbial community associated with the COMP treatment, and with that potential benefits in respect to soil pathogen suppression and other microbial driven functions which are more likely to explain this significant yield response in this system where inorganic fertiliser inputs were applied when required.

The levels of Colwell P (or bicarbonate extractable P) in the treatment soils at the start of crop 6, immediately following the application of the second application of compost for the COMP and MIX treatments are presented in Table 8 and these have implications for the sustainability of this compost based system over the long term. It is apparent in the low initial soil P (i.e. LP) treatments, that the T5-COMP treatment has quite a high mean level of Colwell P with 252 mg kg^{-1} which is almost identical to the FP treatment mean level (Table 8). This high level of extractable P in the soil represents a potential risk to water quality, and as such further applications

Table 8 Mean soil total organic carbon (OC) levels (0–15 cm) for the treatments for the two Capsicum crops (crop 4 and crop 6), and mean soil microbial biomass carbon (MBC), effective cation exchange capacity (eCEC), and Colwell (bicarbonate extractable) P for the crop 6 soil

Treatment	Crop 4	Crop 6			
	Total OC (g 100 g^{-1})	Total OC (g 100 g^{-1})	MBC (μg C/g)	eCEC [cmol(+)/kg]	Colwell P (mg/kg)
T1—FP—HP	1.5 **cd**	1.4 **c**	159 **b**	9.2 **c**	331 (2.52)[a] **a**
T2—COMP—HP	2.1 **a**	3.0 **a**	356 **a**	16.0 **a**	352 (2.55) **a**
T3—MIX—HP	1.6 **cd**	2.3 **b**	203 **b**	11.8 **b**	312 (2.49) **b**
T4—FP—LP	1.4 **de**	1.3 **c**	216 **b**	8.6 **c**	253 (2.40) **c**
T5—COMP—LP	1.9 **b**	3.0 **a**	341 **a**	15.5 **a**	252 (2.40) **c**
T6—MIX—LP	1.6 **c**	2.3 **b**	201 **b**	11.0 **b**	207 (2.32) **d**
T7—Nil control—LP	1.2 **e**	1.1 **c**	142 **b**	6.9 **d**	31 (1.49) **e**
LSD ($P = 0.05$)	0.2	0.3	109	1.5	(0.05)

Different letters within each column indicate a significant difference between treatment means at $P = 0.05$ (from ANOVA using the Fisher F-protected LSD value at 5% significance). Least significant difference value for each crop at $P = 0.05$ ($LSD_{5\%}$) provided. Soil samples taken at planting time for analysis, composite of 7 cores (5 cm diameter)

COMP compost treatments (T2 and T5), *MIX* mixed treatments (T3 and T6), *FP* farmer practice treatment (T1 and T4), *HP* High P (i.e. initial high levels of plant available phosphorus in the soil), *LP* Low P (i.e. initial low levels of plant available phosphorus in the soil)

[a] Log transformed values for Colwell P used in ANOVA in parenthesis

of compost would need to take into account the extractable P levels in the soil and compost for determining the application rate.

Fertiliser savings from compost

The savings in the use of inorganic fertilisers (P, K, dolomite and especially N) achieved by the COMP and MIX treatments can be seen in Table 4. It is evident in Table 4 that the compost inputs to the soil for the COMP and to a lesser extent MIX treatments achieved substantial savings in the amounts of inorganic N (urea) required to be applied to match FP. The COMP treatment required no urea for the first three crops following the 2nd application of compost (i.e. crops 6, 7 and 8) and only the same urea as FP for crops 9 and 10 (Table 4). The COMP treatment received only 55% of the urea received by the FP treatment over the first 10 crops (1138 vs 2071 kg urea ha^{-1}) and only 43% for the 5 crops following the second compost application (380 vs 887 kg urea ha^{-1}). For this point it is also important to note that the urea application for the FP treatment only represented half of the plant available N applied for that treatment with the other half coming from the poultry manure application prior to each crop.

In addition to N, the COMP treatment required no additional phosphorus or potassium inorganic fertiliser, whilst its improved soil CEC and soil buffering capacity (eCEC of 10.4, pH 5.9) from the compost organic matter meant that it did not require the 2 to 3 t ha^{-1} of dolomite of the MIX and FP treatments to raise the soil pH from 5.25 and 4.96 respectively to the desirable pH level of around 6 (Beckingham 2007) for the final sweet corn crop.

Benefit–cost analyses

Benefit–cost analysis (BCA) provided an assessment of the relative economic value of the proposed alternative compost farming systems to the conventional farmer practice for the 10 successive vegetable crops grown in this study from 2005 to 2011. The enterprise budgets compiled for each treatment for each of the 10 vegetable crops of this study are presented in Appendix B (see Supplementary material file), and these formed the basis of the BCA done for this experiment. The flow of costs and returns included in the analysis (see Appendix B, supplementary material file) highlight the important contribution of the yield responses of the high value capsicum crops (crops 4 and 6) to farmer returns for the compost treatments and the overall BCA results.

COMP versus FP treatment

The results of the BCA show that after 10 vegetable crops, the application of the compost for the COMP treatment in the field experiment versus FP resulted in a positive BCR of 3.33 (Table 9). This indicates that the present value of the real net benefits from applying the COMP treatment versus the FP treatments exceeded the present value of the investment (i.e. cost) of applying the compost to the soil. The analysis shows that the initial and subsequent investment in compost for the COMP treatment is recovered and a return on investment greater than the discount rate is achieved. The field experiment results indicate that for every dollar invested in the application of compost as per the COMP treatment in a vegetable production system, $3.33 is returned over 10 vegetable crops. The relative contribution of the compost driven yield response of the capsicum crop (crop 6) to net benefits and increased returns for the COMP treatment in the analysis, is apparent in Table 9.

MIX versus FP treatment

The BCA comparing the MIX and FP treatments over the 10 crops resulted in a BCR of 2.63 (Table 10). Whilst this is slightly lower than the COMP versus FP BCR result, it does indicate that the present value of the real net benefits from applying the MIX compost soil treatment versus the FP treatment still exceeded the present value of the investment (i.e. cost) of applying the compost to the soil over this timeframe. This analysis shows that the initial and subsequent investment in the compost application in the MIX treatment is recovered and a return on investment greater than the discount rate is achieved. The analysis indicates that for every dollar invested in the application of compost as in the MIX treatment in a vegetable production system, $2.63 is returned over 10 vegetable crops (Table 10).

Break-even cost of compost

The break-even point for this analysis occurs where the BCR = 1. The break-even cost of compost for the

Table 9 Benefit–cost analysis of compost versus farmer practice treatment

	Real net benefits ($ ha^{-1})	Real initial cost ($ ha^{-1})	Discounted net benefits ($ ha^{-1})	Discounted initial cost ($ ha^{-1})
1. Broccoli	824	10,179	984	12,143
2. Eggplant	840		983	
3. Cabbage	686		787	
4. Capsicum	7665		8623	
5. Leek	713		787	
6. Capsicum	55,372	12,141	59,890	13,131
7. Broccoli	571		606	
8. Lettuce	4576		4759	
9. Cabbage	5355		5461	
10. Sweet corn	1252		1252	
	Present value benefits ($ ha^{-1})		84,130	
	Present value costs ($ ha^{-1})			25,275
	Net present value ($ ha^{-1})		58,856	
	BCR[a]		3.33	
	IRR (%)		48	

[a] *BCR* benefit–cost ratio

Table 10 Benefit–cost analysis of mixed versus farmer practice treatment

	Real net benefits ($ ha^{-1})	Real initial cost ($ ha^{-1})	Discounted net benefits ($ ha^{-1})	Discounted initial cost ($ ha^{-1})
1. Broccoli	319	5089	381	6072
2. Eggplant	261		306	
3. Cabbage	323		370	
4. Capsicum	− 3082		− 3466	
5. Leek	− 4087		− 4509	
6. Capsicum	29,721	6070	32,146	6566
7. Broccoli	245		259	
8. Lettuce	1960		2039	
9. Cabbage	5163		5266	
10. Sweet corn	413		413	
	Present value benefits ($ ha^{-1})		33,205	
	Present value costs ($ ha^{-1})			12,637
	Net present value ($ ha^{-1})		20,568	
	BCR[a]		2.63	
	IRR (%)		28	

[a] *BCR* benefit–cost ratio

analysis comparing the COMP soil treatment to FP was calculated to occur when the compost cost $131 m^{-3} (when applied prior to crop 1 and crop 6). The break-even cost of the compost for the analysis comparing the MIX treatment to FP was calculated to occur when the compost cost $104 m^{-3}. These results reflect the influences of the higher yield response for the COMP treatment compared to MIX, as well as the additional chemical fertiliser inputs that are part of the MIX treatment compared to the COMP treatment farming system.

Discussion

Crop yield response to compost

Our results demonstrate the potential role that green-waste compost may have as a soil amendment, to help close the yield gap between current and maximum potential yield for crops that respond to improved soil-quality conditions. The closing of the yield gap has been proposed as a focal point for efforts to lift world food production and improve food security (Lobell et al. 2009; Pradhan et al. 2015).

The yield results from this experiment demonstrated that the COMP treatment matched or bettered the yields of the comparable FP treatment for all crops following the first application of 125 dry t ha^{-1} of compost (prior to crop 1) as well as all of the crops following the repeat application of compost (prior to crop 6). It demonstrated that on the basis of crop yield, a farming system involving a large single application of compost (with application rate based on the N requirement of the first crop) applied every five crops (supplemented with N as urea when required) could match the current farmer practice (FP treatment) where crop nutrients are supplied through chicken manure and soluble inorganic fertilisers.

The response of the capsicum crop when planted as the first crop following the second application of compost was substantial, producing a yield which was almost double that of the FP treatment. This yield of around 60 t ha^{-1} was 50% higher than the crops previously perceived maximum potential yield (Bartha 1983) and was due to the COMP treatment plots achieving almost the maximum number of harvestable fruit per plant. This yield response was much more substantial than that achieved for the capsicum plant grown as the 4th crop following the first compost application (i.e. 25% increase). Perhaps reflecting the effect of time from compost application and/or the benefits of repeat application on soil quality and yield. There were certainly significant differences ($P < 0.05$) between the treatments for soil total organic carbon (TOC) content at the crop 6 planting, with the soil OC levels for the COMP, MIX and FP treatments being 3.0, 2.3, and 1.4 g 100 g^{-1} respectively (see Table 8). This increase in soil TOC from the compost was also accompanied by a significant increase in soil microbial biomass C (MBC) for the capsicum crop following the second application of compost (see Table 8) and this has been reported to persist in subsequent crops at this experiment(Donovan et al. 2014). There were also benefits to soil structure from the compost inputs in this experiment with a significant increase in the percentage water stable aggregates in the COMP and MIX treatments (Eldridge et al. 2014a, b) relative to the FP treatment. It is therefore likely that improvements in these properties and/or improvements in other beneficial microbial properties relating to these changes have contributed to these yield responses. Other beneficial microbial properties relating to the increased organic carbon from the compost that may have also contributed to the crop yield responses might include enzyme activity and microbial composition influencing the nutrient cycling in the soil (Kremer and Hezel 2013; Reeve et al. 2010) as well as the microbial supression of some soil-borne pathogens for crops (Pane et al. 2013; Suárez-Estrella et al. 2013; Termorshuizen et al. 2006). These benefits were also evident for the MIX treatment with its compost rate half that of the COMP treatment, where it achieved comparable yields to FP for most crops and then in the case of T6, a mean marketable yield for the second capsicum crop that was not significantly different to the COMP treatment, but significantly higher than FP.

As such, the crop yield results of our study provide some support to our original hypothesis 1, by demonstrating that such compost based systems can at least match the farmer practice system in terms of crop yield for all crops, but then achieve significantly higher yields for some specific crops that are responsive to the associated soil quality improvements. Our results also support hypothesis 3, regarding improved yield benefits from repeat applications of compost, but only for those crops that are responsive to the compost applications and associated soil quality improvements (e.g. capsicum). Our results indicate that the impact of the large applications of compost on soil quality particularly in respect of soil TOC and microbial biomass C and other associated soil quality parameters (e.g. pathogen suppression, enzyme activity) is the most likely mechanism for the substantial yield response observed the capsicum crop following the second application of compost. The fact that this yield response was well above the average district yield and the previously perceived maximum yield for this crop variety grown in this area with high fertiliser nutrient inputs, also tends to support this conclusion.

Our study demonstrated a ‘yield-gap-closing’ response from capsicum to compost induced soil quality improvements in a soil with a hard-setting soil constraint, but this may not apply to other soil types with different constraints and as such, further evaluation is required for different soil types.

Inorganic N fertiliser savings from compost and soil processes

This study is one of the first to demonstrate that the periodic application of large quantities of compost to the soil to improve soil quality and health can actually be a profitable option for peri-urban vegetable growers, when integrated with supplementary inputs of inorganic N fertiliser when required as part of a production system.

The significant savings achieved by the COMP treatment for required urea fertiliser inputs relative to FP demonstrates the capacity of this green waste compost (derived from green waste garden organics and 10–20% poultry manure) to provide sufficient plant available N from the mineralisation of its own organic N content as well as from the benefits associated with improvements to the retention and cycling of mineral N released from the soil, crop residues and any urea when applied. Since the residues from these vegetable crops mostly had C/N ratios of < 15 (Rahn and Lillywhite 2001), their impact would have been mainly positive in terms of the levels of mineral N in the soil with minimal contribution to N immobilisation or drawdown. Certainly N immobilisation was not apparent in the mineral N levels in the soils at planting for the crops of this study, presented in Eldridge et al. (2014a, b). A long term incubation study of a number of composts in soil by Eldridge et al. (2017) demonstrated that composts of pure green waste produced net N immobilisation in the soil for the first 12 months following application, whilst other blended composts from green waste with ~ 10% manure or biosolids released ~ 10% of their total N as *mineral* N in the first 12 months. This will influence the amount and time that inorganic urea is required to be applied in this system. Certainly a number of studies (Dalal et al. 2010; Vaughan et al. 2011; De Rosa et al. 2016) have demonstrated that green waste compost applications can reduce greenhouse gas emissions from agricultural soils, largely through N immobilisation by soil microbes and associated increases in N cycling in these soils.

The economic case for compost based vegetable production systems

The field experiment BCA finding that the COMP and MIX treatments compared favourably with the current conventional farmer practice treatment (FP) over 10 crops with BCR values of 3.33 and 2.63 respectively, demonstrates the economic viability of these systems. It is important to note the dominant contribution of the capsicum crop yield response to the repeat compost application to this positive BCA outcome for both the COMP and MIX treatments. This is particularly evident when one considers that the BCA for the first five crops of this field experiment found a negative BCR for the MIX treatment and a BCR of only 1 for the Compost treatment (Chan et al. 2011). The results of this earlier analysis led Chan et al. (2011) to conclude that the large compost application (125 dry t ha^{-1}) had paid for itself over five vegetable crops, but with additional benefits for soil quality and the environment. The BCA results from this experiment demonstrate that although COMP and MIX treatments only achieved a BCR of 1 and < 1 compared to FP for the first 5 crop cycle (Chan et al. 2011) the economic benefits from the 5 crop cycle following the repeat application of compost was substantial, delivering these treatments BCR values of 3.3 and 2.6 respectively for the whole 10 crops. Our results support our original study hypotheses 2 and 3, as over two cycles of 5 crops including two one off applications of green waste compost, the two compost treatments of our study (COMP and MIX) were found to achieve higher farm incomes than farmer practice (FP), and this was more pronounced following the repeat applications of compost.

It is important to note that both the COMP and MIX treatments studied in this field experiment represent two ways of using compost integrated with inorganic soluble chemical fertilisers, rather than applying compost on its own as a single soil amendment. Supplementary N fertiliser was certainly required in this experiment for the COMP treatment, where it was applied from the third crop following the first application of compost and then from the fourth crop following the second repeat application of compost. The COMP treatment compared to the FP treatment achieved real fertiliser savings using 40% less inorganic N (urea), and 100% less inorganic P and K fertiliser. The MIX treatment received urea as well as inorganic P and K at the farmer practice rate or less for all crops. This did represent a plant nutrient use efficiency gain for the MIX treatment relative to the FP treatment, as FP received NPK present in the poultry manure applications for each crop in addition to the NPK as inorganic fertiliser inputs.

The fore mentioned fertiliser savings were taken into account in the economic analysis in terms of their purchase cost savings. But other aspects of this saving, such as the saving on greenhouse gas (GHG) emissions relating to the production of those inorganic fertilisers as well as from the diversion of green waste from landfill to compost and then agricultural soil (Lundie and Peters 2005) were not. Also, no economic value, apart from that reflected in crop yield, was attributed to the numerous improvements to soil quality and function that were associated with the COMP treatments in this experiment, such as improved soil biological health (Donovan et al. 2014), soil chemistry and soil physical quality (Chan et al. 2008; Eldridge et al. 2014a, b), as well as water quality (Chan et al. 2010; Dougherty and Chan 2014). Such factors might be included in future analyses if there is a shift towards a new paradigm of ecological economics as discussed by Costanza et al. (2015).

The environmental sustainability of compost vegetable production systems

The environmental sustainability of these systems over time is another factor which needs to be taken into account when pondering the results of the BCA for the treatments in this field experiment. For this experiment, it was the accumulation of high levels of extractable P in the soils from these treatments which was the first factor to present itself as a potential risk to the environment (i.e. water quality), requiring these practices to be modified over time. The levels of extractable P were found to be quite high (~ 250 mg kg^{-1}) in the COMP treatment at the start of crop 6 (Table 8) and still represented a potential risk to water quality, though less than FP (Dougherty and Chan 2014). It is important to note that reason for the elevated level of Colwell P in the crop 6 soil was the higher Colwell P content in the 2nd batch of compost that was applied at this experiment (Table 1). It is therefore important to monitor soil available P levels over time and factor in the P content of compost and soil, in addition to crop requirements, when determining acceptable compost application rates within these systems over the longer term to avoid adverse environmental outcomes.

With this information on Soil P accumulation and the BCA results from this study in mind, our current knowledge would suggest the best approach for using this compost might be to begin with a large compost application based on crop N requirement (i.e. ~ 120 dry t ha^{-1}) to transform soil quality and microbiology, and then follow up with a more moderate application (i.e. ~ 60 dry t ha^{-1}) after 5 crops or so to still get an economic benefit. Then after that consider periodic smaller applications that aim to maintain a soil OC level at minimum level (e.g. 2%). Such applications will need to take soil and compost nutrient levels into account, especially in respect of available P content. In addition selection of composts with lower extractable P levels may need to be a consideration for composts used in the later phases of this system. Certainly, our study would suggest that an integrated approach which allows supplementary inputs of inorganic fertiliser, especially N fertiliser, when tests (e.g. petiole sap test) suggest it is required, is necessary. Further research is required to further refine this compost based production model for peri-urban vegetable production, in order to optimise benefits for the growers and the environment.

The implications of SDG 12 and food waste policy for compost based peri-urban vegetable production systems

It is important to note that the quantity and nature of composts generated from municipal organic wastes is also likely to change over time as more and more food waste is captured and diverted away from landfill to composting facilities, as nations respond to the United Nations Sustainable Development Goal 12 from the 'Transforming our world: 2030 Agenda for Sustainable Development' (United Nations General Assembly 2015). Australia for example, in response to Goal 12—'ensure sustainable consumption and production patterns', has developed a 'National Food Waste Strategy' which aims to halve food waste by 2030 and encourages local government waste services to add household food scraps to their current source-separated curb-side collection of garden organics and divert food waste away from landfill to composting facilities (Commonwealth of Australia 2017). As such, one would expect that this policy will result in initially increasing the proportion of inputs of food waste to green waste compost as the capture and diversion of food waste from household waste increases to a maximum, followed then by decline as other policies encourage education to reduce the overall quantity of food waste generated in Australia. Such changes in the proportion of food waste to garden organics may change the nature of the final compost products and this will need to be studied and taken into account for management recommendations to growers. Likewise these government policies will eventually result in the generation of much larger quantities of green waste compost from large urban centres for agriculture. Peri-urban horticulture offers an opportunity to utilise these products as part of a more sustainable food production system based on urban source-separated green-waste compost inputs supplemented with inorganic chemical fertilisers. This is especially so when one considers the dominant contribution of the cost of transportation-cartage of the compost to the farm-gate price of compost. This, in the absence of any subsidy, affectively confines the profitable use of compost to those agricultural enterprises which are located within close proximity to the source or supplier, and hence the suitability of peri-urban agriculture with high value horticultural crops such as vegetables.

This study demonstrated the potential of green-waste compost to lift the yield of an agricultural crop, in this case capsicum, to above what is generally accepted as its maximum potential yield value in a hard-setting agricultural soil. This is an example of closing the yield gap by improving soil quality (Lal 2004, 2010) with an organic soil amendment. If such organic soil amendments are found to help close the 'yield gap' for other important crops, especially staple crops, then there is real potential for improving food security as well as the sustainability of food production systems through such improvements to soil quality.

Conclusions

This study has proven that peri-urban vegetable production systems based on periodic large one off applications of green waste compost (i.e. 62.5 and 125 dry t ha^{-1}) supplemented with inorganic fertilisers (especially N) when required, can match and in some cases better current farmer practice in terms of marketable yield over 10 crops. A detailed economic analysis of the field experiment revealed that such compost based systems can achieve significant economic benefits for farmers and that these benefits can increase with follow up compost applications. Many studies have demonstrated the causal link between compost inputs and improvements in soil quality, but this study is one of the first to demonstrate that this can also translate into yield benefits and fertiliser savings and as a consequence, improved farmer profits.

The substantial increase in marketable yield for the second capsicum crop from the compost treatment in this experiment (i.e. ~ 90% increase on farmer best practice and ~ 50% above perceived maximum crop yield) provided a classic example of closing the 'yield gap' by improving soil quality with an organic amendment. This long term field experiment has demonstrated real tangible food production and economic benefits from utilising compost made from green-waste sourced from nearby urban areas in peri-urban vegetable production.

Acknowledgements The long term compost vegetable field trial was a joint research and development project of NSW Department of Primary Industries (2005–2013), with collaboration and funding support from the Australian Centre for International Agricultural Research (ACIAR) (Project no. HORT/2007/066/1, 2008–2012), Horticulture Innovation Australia (HIA) (Project no. VG09038, 2010–2013), and NSW Department of Environment and Climate Change (2004–2008). The contributions of Leigh James, Bill Yiasoumi and Chris Dorahy are gratefully acknowledged. Thank you also to Anthea McClintock (NSW DPI) for some final adjustments for the benefit–cost analysis and Robyn Hean (NSW DPI) who reviewed the original draft, making many useful comments and suggestions which helped to greatly improve the paper. The invaluable contributions of Stuart Tyler, Darren Fahey and Lynette Muirhead in providing technical support for the running of this field experiment over the time period documented in this paper is gratefully acknowledged. Thank you also to Brett Enman, Ildiko Meszaros, Kamal Hossain, Deirdre Harvey, Adrian Graham, Adam Pirie, Ian McMaster, Motiul Oader, and Phil Pengelly for field assistance.

Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest.

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