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Biochar and Compost Increase Crop Yields but the Effect is Short Term on Sandplain Soils of Western Australia

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ABSTRACT

Sandplain soils on the south coast of Western Australia have low inherent fertility, which is mainly due to poor nutrient retention caused by insufficient clay and organic colloidal material. Previous research has shown the benefits in nutrient levels and retention from adding clay to sandplain soils; however, there is almost no information on the addition of organic amendments. A field experiment was established at the Esperance Downs Research Station, Western Australian, in March 2010, to assess the effects of wheat straw (WS) and chicken manure (CM) biochars and compost with and without phosphorus (P) addition on soil properties and crop production over five growing seasons. The five seasons alternated between winter and summer crops. The ~~biochar~~ and compost treatments significantly increased crop yields and P uptake in 3, 2 and 1 of the five seasons, respectively. The yield increases ($P < 0.05$) were no more than 8%. By the end of the third season, no differences in crop yields were found that could be attributed to the organic amendments. The addition of P increased crop yields in each winter cropping season. Phosphorus addition explained more than 30% of the variation in crop yields. Despite marginal P levels and summer drought conditions, arbuscular mycorrhizal root colonisation was not affected by the organic amendments. There were no significant interactions between the organic amendments and P addition in terms of crop yields, P uptake or P uptake efficiency. We conclude that much of the effect of the organic amendments was due to direct nutrient addition which dissipated over time.

CM, WS/

Key Words: mycorrhizal root colonisation, nutrient retention, organic amendments, P addition, P uptake

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INTRODUCTION

The sandplain soils on the south coast of Western Australia have low inherent fertility due to soil properties that limit nutrient retention (Moore, 2004). This is a reflection of the high sand (> 95%) and inherently low colloidal (clay and organic matter) content of these soils resulting in low surfaces areas and charge densities. The cation exchange capacity (CEC) of topsoils commonly ranges from 2 to 4 $cmol_+ kg^{-1}$. Together, soil organic carbon (C) and clay explain more than 80% of the variation in CEC in sandplain topsoils (Hall *et al.*, 2010) even though they represent less than 4% of the soil mass. The issues associated with poor nutrient retention are not just limited to the south coast of Western Australia. More than 70% of the wheatbelt soils in Western Australia have very low (< 5 $cmol_+ kg^{-1}$) CEC and approximately 50% of the wheat-growing soils within the states of South Australia and Victoria also have low to very low CEC.

Increasing soil C through management in agricultural systems is a slow process, which is limited by the amount of biomass returned to the soil, the nutrient composition of the biomass (Kirkby *et al.*, 2011) and the degree to which the soil C is exposed or protected from microbial oxidation (Hoyle *et al.*, 2011). In Australian dryland farming systems where minimum tillage and stubble retention have been practiced for many years, the increase in C storage is often small (Chan *et al.*, 2003). This is particularly so for sandy textured soils where the turnover of soil organic C is more rapid than soils with higher clay content (Hoyle *et al.*, 2011). Hence, management options to increase C in sandy textured soils are often limited (Alvarez, 2005) in the absence of quantum increases in carbon inputs and retention.

Adding stable C in the form of biochar to soils has the potential to increase CEC and nutrient retention in sands (Liang *et al.*, 2006, Dempster *et al.*, 2012). Organic amendments can also increase the supply of nutrients to plants directly through nutrient additions (Chan and Xu, 2009) or indirectly through changes in

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soil pH (Van Zwieten *et al.*, 2010) and the activity of biota that enhance plant nutrient availability (Lehmann *et al.*, 2011). There is considerable evidence that biochars promote mycorrhizal activity resulting in enhanced nutrient uptake and use efficiencies in comparatively infertile soils (Bolan, 1991; Warnock *et al.*, 2007; Blackwell *et al.*, 2010; Hammer *et al.*, 2014). The economics of applying biochar to broad-acre dry land farming systems have been found to be profitable where there are substantial savings in inorganic fertilizer inputs (> 50%) and consistent yield increases of 10% over 12 years (Blackwell *et al.*, 2010). There have been many experiments evaluating different biochar feed stocks, pyrolysis temperatures and rates of application; however, very few field experiments have investigated the longer-term effects of biochars and compost on crop production and soil properties.

This study aimed to assess the effects of contrasting organic amendments (compost and biochar) and phosphorus (P) nutrition on winter and summer crop growth in soils that have inherently low nutrient retention and levels of P. Key aims of this study were to determine i) the long-term effects of organic amendments on crop production, ii) the relative effects of organic amendments on soil nutrition and soil biology and iii) the long-term effects of the organic amendments on soil chemistry.

MATERIALS AND METHODS

A field experiment was established at the Esperance Downs Research Station (33.611° S, 121.784° E), on the south coast of Western Australia in May 2010. The site had been rotationally cropped and grazed for more than 20 years. The experiment consisted of four organic amendment treatments (control, compost, wheat straw (WS) biochar and chicken manure (CM) biochar), each with (+P) or without added P fertilizer (–P). The eight treatments were replicated four times in a randomised block design with each plot being 20 m long by 3 m wide. The soils are part of the Fleming series (Overheu *et al.*, 1993) and are classified as mesonatric yellow Sodosols according to the Australian Soil Classification system (Isbell *et al.*, 2002). The soil profile had 80 cm of fine sand over a mottled kaolinitic clay layer.

The WS and CM biochars were made by the Pacific Pyrolysis Pty Ltd. (Somersby, Australia). Each biochar was manufactured at 450 °C to optimise C, nutrients and ion exchange properties (Chan and Xu, 2009). Water was added to the biochars to reduce dust and ignition risks post pyrolysis. The biochars were drilled into the soil using a modified small-plot seeding machine to a depth of 10 cm. The modified seeding machine had a manually metered hopper with vertical hoses to the tynes that aimed to minimise blockages. Three passes per plot were required to deliver the required rate of biochar. The compost was prepared from wheat straw (31%), canola straw (31%), grain seconds (21%), pig manure/straw bedding (9%), and subsoil clay (8%). The compost was manufactured over a 10-week period using commercial equipment. The linear piles of feedstock were mechanically aerated and watered at times dictated by oxygen and moisture levels. The humified compost was surface spread onto the plots. The gravimetric water contents of the raw WS biochar, CM biochar and compost amendments were 690, 290 and 260 g kg^{-1}, respectively. The amounts of raw biochars and compost added to the soil were adjusted for water content to give application rates of 5 t dry weight ha^{-1}. This application rate was found to be near the optimal rate of application when banded in field experiments at Moora (Blackwell *et al.*, 2010). The control and compost-treated plots were subsequently tilled with three passes of the biochar banding unit to even out tillage differences among the treatments.

The –P treatment received no added P for the duration of the experiment, whereas the +P treatments received sufficient soluble P to grow a 4 t ha^{-1} cereal and 3 t ha^{-1} lupin crop. The fertiliser P (11–14 kg ha^{-1}) was applied at seeding of the winter crops only. Wheat (*Triticum aestivum* L. var. Mace and Sapphire) and lupin (*Lupinus angustifolius* L. var. Jenabillup) crops were grown in alternate seasons between May and December 2010, 2011 and 2012. A summer forage crop, sorghum (*Sorghum bicolour* (L.) Moench) × sudan-grass (*Sorghum sudanense* (Piper) Stapf.) hybrid (cv. BettaGraze)), was grown between late December and April 2010–2011 and 2011–2012. Crops were sown with minimal soil disturbance on a-23 cm row spacing using a cone seeder with knife points and press wheels. Fertilizer (with the exception of P) applications and pesticide applications for weed and insect control were identical for all treatments. Nitrogen (N), P, potassium (K) and sulphur (S) were applied at rates to satisfy demand for wheat and lupin crops yielding 4 and 3 t ha^{-1}, respectively. In all cases, P was applied as a blend of N:P:S. Additional N and S were applied to the –P treatment in the form of ammonium sulphate and urea so that the total amounts of N and S applied were the same across all treatments. Potassium was applied to all treatments as muriate of potash (KCl). Crop emergence was measured three weeks after seeding. Dry matter samples were collected periodically for the winter and summer forage crops by hand harvesting three 0.5-m^2 quadrats per plot. The wheat and lupin crops were mechanically harvested for grain weights with subsamples retained for grain quality analysis. The sorghum crops were sampled for dry matter and then slashed in mid-March and early May 2011 and in mid-April 2012. All trash from the summer crops was raked from the plots. In 2010–2011, the amount of P removed in the trash was on average 2.6 kg ha^{-1} (range 1.5–3.6 kg ha^{-1}). Key management dates and inputs are given in Table I.

Plant (leaf and grain) nutrient and soil chemical analyses were conducted at the CSBP Laboratories (Perth, Australia) using the same methods outlined by You *et al.* (1999). Soil samples were collected by auger (50 mm in outside diameter) to a depth of 10 cm at thirty locations within each plot at the end of the experiment in January 2012. All samples were collected within the crop rows where the biochar was initially applied. The soils were dried at 70 °C over two days, thoroughly mixed and subsampled prior to being analysed. Soil tests included EC, pH in calcium chloride (1:5), Colwell P and K (0.5 mol L^{-1} $NaHCO_3$ extraction), S (0.25 mol L^{-1} KCl extraction at 40 °C), organic C (Walkley-Black method), exchangeable cations (0.1 mol L^{-1} $BaCl_2$ extraction) and Cu, Fe, Mn and Zn (ethylene diamine tetraacetic acid (EDTA) extraction). Plants, comprising whole stems (2010 and 2010–2011) and wheat flag leaves (2012), were sampled at early anthesis. Sorghum was sampled when plants had reached a height of 50 cm. Plant tissues were subsampled from bulk biomass samples collected within each plot. Lupin seed was analysed post-harvest. Except for the lupin seed, plant samples were dried at 70 °C for 48 h prior to being sent away for analysis. Boron, Cu, Zn, Mn, Fe, Ca, Mg, Na, K, P and S were measured by inductively coupled plasma optical emission spectrometry (McQuaker *et al.*, 1979). Nitrate (NO_3), and ammonium (NH_4) were measured colorimetrically using a flow injection analyser (Zall *et al.*, 1956). Total N was measured using a combustion furnace (Bremner and Mulvaney, 1982)

Phosphorus uptake (kg P ha^{-1}) was calculated by multiplying total biomass (kg ha^{-1}) at anthesis by the P concentration in the dry sample. Phosphorus uptake efficiency is the total biomass (kg ha^{-1}) divided by P uptake. For the 2012 wheat crop, P was measured in the flag leaf as opposed to the whole shoot. Flag leaf P was used to calculate P uptake and P use efficiency with the assumption that flag leaf and whole shoot P levels at anthesis were similar. Data recalculated from Batten *et al.* (1986) showed minor differences in total P (± 0.01%) between flag leaves and whole shoots at anthesis.

Mycorrhizal populations were measured in sorghum roots in May 2011 using methods described by Solaiman *et al.* (2010). Six whole plants were extracted from each plot. Individual plants were encircled and removed with a trenching spade inserted to a depth of 300 mm. Aboveground biomass was removed leaving the roots which were immediately placed in cool (< 3 °C) storage awaiting analysis. Approximately 300 mg of roots were removed from each paired sample and stained with Trypan Blue. The roots were placed in solution on a gridded Petri plate and the number of grid nodes that were infected with arbuscular mycorrhiza (AM) was recorded using a light microscope. Six replicate measurements were made on each sample. Mycorrhizal colonisation is presented as a percentage of root length.

The rainfall-limited yield potential of wheat was calculated using the method of Oliver *et al.* (2009) which takes into account the summer rainfall and the soil water storage capacity. The transpiration efficie-

TABLE I

Crop type and variety, sowing and harvest dates, sowing and fertilizer application rates and seasonal rainfall (sowing–harvest) during the field experiment

Crop	Sowing date	Harvest date	Sowing rate	Fertilizer rate					Seasonal rainfall
				Treatment without P addition			Treatment with P addition		
				N	K	S	N P S	K	
			kg ha^{-1}						mm
Wheat (cv. Sapphire)	May 27, 2010	Dec. 14, 2010	80	92	15	9	92 14 9	15	290
Sorghum (cv. BettaGraze)	Dec. 29, 2010	Mar. 3, 2011	16	0	0	0	0:0:0	0	123
Lupin (cv. Jenabillup)	Jun. 2, 2011	Dec. 19, 2011	100	4	30	7	4:11:7	30	404
Sorghum (cv. BettaGraze)	Dec. 22, 2011	Apr. 18, 2012	16	24	0	0	24:0:0	0	110
Wheat (cv. Mace)	Jun. 5, 2012	Nov. 22, 2012	90	92	16	9	92:12:9	16	242

Use same format (with space between columns) as for -P rates ncies used were 20 kg mm^{-1} ha^{-1} for wheat and 15 kg mm^{-1} ha^{-1} for lupin.

Treatments means were statistically compared using the general analysis of variance function in Genstat (16th edition, VSN International, Hemel Hempstead, UK). The factorial design of the experiment allowed individual and main treatments to be tested. Where there are no interactions between the main treatments, main treatment means are presented. Otherwise, the statistical differences among individual treatment means are presented.

RESULTS

The chemical properties of the raw biochars, compost and surface soil used in the experiment are given in Table II. The biochars, compost and soil were alkaline, neutral and acidic, respectively. The organic C contents of the biochars (380 and 530 g kg^{-1}) were approximately twice that of the compost and 40 times higher than that of the soil. The biochars also contained markedly higher levels of nutrients (N, P, K and S) compared to the compost. The nutrient levels of both the compost and biochar were orders of magnitude higher than those of the soil. Between the two biochars there were considerable differences in nutrient levels. The WS biochar was more alkaline, had higher C, N, K and CEC than the CM biochar. Conversely, the CM biochar contained two times more P, six times more Zn and almost two times more S than WS biochar (Table II).

No significant differences in plant numbers at emergence were found between the treatments for the duration of the experiment. In each case, plant numbers were adequate to achieve maximum yields, with values for the cereal, lupin and sorghum crops being consistently greater than 90, 30 and 10 plants m^{-2}.

Extractable soil P and plant P concentrations were at the lower ends of the adequate ranges at 10–14 and 2.2–2.8 mg kg^{-1} respectively, throughout the experiment. Plant P (PP) explained 33% of the variation in wheat grain yield (GY, t ha^{-1}) in 2012 ($GY = 1.426 \ln PP + 5.46$, $n = 36$). The addition of soluble P (+P treatments) significantly increased wheat and lupin grain yields in each year of the experiment by 0.32 to 0.4 t ha^{-1} when compared to the –P treatments (Table III). The addition of P to the winter crops had no significant effect on biomass yields in the subsequent summer forage sorghum crops. In each year the differences in sorghum biomass yield between the +P and –P treatments was less than 0.2 t ha^{-1} (Table III).

All organic amendments increased wheat grain yields ($P < 0.05$) in 2010 by 0.3–0.4 t ha^{-1}. There was no difference in yield between the compost and biochar treatments (Table III). Yields of the subsequent summer forage crop sorghum were increased only by the WS and CM biochar treatments when compared to the control during the summer and early autumn of 2010–2011. The WS biochar treatment had significantly more biomass than all other treatments (Table III). Lupin grain yields were increased ($P < 0.05$) only by the CM biochar treatment when compared to the control in 2011 by 0.38 t ha^{-1}. There were no differences in lupin grain yield between the control, compost and WS biochar treatments. The sorghum (2011–2012) and wheat (2012) crops had no significant differences in yield (biomass and grain) between the compost treatment, the biochar treatments and the control (Table III). The wheat and lupin grain yields achieved more than 80% (81%–93%) of the rainfall-limited yield potential and were markedly higher than the average district yields. There were no differences in wheat quality among the main treatments in terms of protein, moisture, gluten and falling numbers in 2010 (data not shown). However, screenings were affected by P addition with the +P treatment having higher ($P < 0.01$) values than the –P treatment at 11% and 10%, respectively. There were no differences in lupin

TABLE II

Chemical properties of the organic amendments and sandplain soil (0–10 cm) used in the experiment

Property	Wheat straw biochar	Chicken manure biochar	Compost	Soil [a]
pH	8.4	7.8	6.9	4.8
Organic C (g kg^{-1})	530	380	250	12
Total N (g kg^{-1})	27	15	9	1
Total P (mg kg^{-1})	5 100	15 400	1 300	11–14
Total K (mg kg^{-1})	64 000	17 000	8 000	60
Total S (mg kg^{-1})	2 000	3 500	1 200	10
Total Zn (mg kg^{-1})	50	380	100	0.38
Cation exchange capacity ($cmol_+$ kg^{-1})	41	36	–	2–3

a) For soil, the P, K and S values are extractable fractions by 0.5M $NaHCO_3$ (P and K) and 0.25M KCl.

TABLE III

Grain yields of the winter wheat and lupin crops and dry matter yields of the summer forage sorghum crops as affected by the P and organic amendment main treatments and the calculated rainfall-limited yield potential (YP)

Main treatment	Wheat grain yield in 2010	Sorghum dry matter yield in 2010–2011	Lupin grain yield in 2011	Sorghum dry matter yield in 2011–2012	Wheat grain yield in 2012
	$t\ ha^{-1}$				
–P	4.9[a)]a[b)]	1.28	2.54a	4.07	3.50a
+P	5.3b	1.37	2.91b	4.24	3.82b
Level of significance	$P < 0.001$	ns[c)]	$P < 0.001$	ns	$P < 0.001$
Control	4.8a	1.16 a	2.68a	3.75	3.66
Compost	5.1b	1.23ab	2.65a	4.26	3.73
Wheat straw biochar	5.1b	1.54 c	2.50a	4.15	3.62
Chicken manure biochar	5.2b	1.36 b	3.06b	4.45	3.63
Level of significance	$P = 0.005$	$P < 0.001$	$P < 0.002$	ns	ns
YP ($t\ ha^{-1}$)[d)]	5.7	–	3.3	–	4.3

a)Values are means ($n = 32$).
b)Means followed by different letters in a column within the P main treatments or the amendment main treatments are significantly different at $P < 0.05$.
c)Not significant.
d)Calculated using the method of Oliver *et al.* (2009) which takes into account the summer rainfall and the soil water storage capacity.

grain protein among the treatments. In 2012, wheat protein was reduced by 0.4% in the WS biochar and +P treatments when compared to the control and the –P treatment, respectively. Despite this, the absolute differences were small and resulted in differing segregations based on wheat grain delivery standards.

Phosphorus levels in wheat and sorghum biomass were increased ($P < 0.01$) as a result of the +P treatment compared to the –P treatment. Conversely, there was no difference in P levels in lupin seed for the +P and –P treatments (Table IV). Phosphorus uptake in wheat and sorghum biomass and in lupin seed was increased in the +P treatment for all crops and years when compared to the P treatment. No difference in P levels was found in wheat biomass in 2010 among the organic amendments. However, P uptake was increased in the compost and CM biochar treatments compared to the control (Table IV). Both P levels and P uptake were increased by the WS biochar and CM treatments in the forage sorghum crops when measured in March 2011. The mycorrhizal colonisation measured in sorghum roots showed no differences among the organically amended treatments. There were no treatment differences in P levels within lupin seed (2011) and wheat biomass (2012). However, P uptake in lupin seed was higher ($P < 0.01$) for the WS biochar and CM treatments when compared to the control. The P levels in the plant tissues were marginal for each crop, being equal to or near the critical threshold value (Table IV).

No differences were found between the main treatments in Cu, NH_4, S, CEC, organic C and pH for the soil samples collected to a depth of 10 cm at the completion of the experiment in January 2013 (Table V). However, the +P treatment had higher ($P < 0.01$) P, K and Zn levels compared to the –P treatment. Trace levels of Zn (0.2%) and Cu (0.1%) were applied within the compound (N:P:S) fertilizer in the +P treatment. Only soil NO_3 was higher ($P < 0.05$) in the compost treatment compared to the control (Table V). The biochar treatments had no measurable effect on soil chemical properties three years after being applied.

Despite significant nutrient differences in plant parts occurring between the main treatments in the sorghum, lupin and wheat crops, all values of the P levels within the plant tissues were in the range adequate for optimal crop production (Table VI).

Economic value of the organic amendments

The increase in profitability, calculated as net present value, for the CM biochar, WS biochar and compost treatments over the control was 216, 30 and 90 Australian dollar (AUD) ha^{-1}, respectively, when discounted at a rate of 6% over the three years of the experiment. The break even cost of the organic amendments therefore ranged from 6 to 47 AUD t^{-1} when applied at rates of 5 t ha^{-1}.

DISCUSSION

The chemical composition of biochars is dependent on feedstock and pyrolysis temperature (Chan and Xu, 2009; Singh *et al.*, 2010). The lower pyrolysis temperatures (*i.e.*, < 500 °C) that were used to produce the

TABLE IV

Effect of biochar and compost treatments on P levels, P uptake, P uptake efficiency and root mycorrhizal colonisation of the winter wheat and lupin crops and the summer forage sorghum crops

Main treatment	Wheat in 2010			Sorghum in 2010–2011				Lupin in 2011			Wheat in 2012		
	P level in dry biomass	P uptake in biomass	P uptake efficiency in dry biomass	P level in dry biomass	P uptake in biomass	Mycorrhizal colonisation of roots	P uptake efficiency in dry biomass	P level in dry seed	P uptake in seed	P uptake efficiency in dry ~~grain~~ seed	P level in dry flag leaf	P uptake in biomass[a]	P uptake efficiency in dry biomass[a]
	g P kg^{-1}	kg P ha^{-1}	kg kg^{-1} P	g P kg^{-1}	kg P ha^{-1}	%	kg kg^{-1} P	g P kg^{-1}	kg P ha^{-1}	kg kg^{-1} P	g P kg^{-1}	kg P ha^{-1}	kg kg^{-1} P
–P	3.7[b]a[c]	24.36	492	1.9a	2.42a	28.7	532.9	2.4	6.06a	419.8	2.7a	21.69a	370.72
+P	4.1b	28.69	412	2.0b	2.77b	26.0	497.9	2.5	7.13b	410.0	3.2b	27.43b	317.67
Level of significance	$P < 0.001$	$P < 0.03$	ns[d]	$P < 0.01$	$P < 0.01$	ns	$P < 0.02$	ns	$P < 0.001$	ns	$P < 0.01$	$P < 0.001$	$P < 0.01$
Control	3.7	21.76a	516	1.8a	2.13a	25.6	550.9	2.4	6.38a	422.5	2.9	23.66	345.92
Compost	4.0	27.33b	431	1.9ab	2.36a	32.1	524.9	2.4	6.47a	411.6	3.0	26.30	334.88
Wheat straw biochar	3.9	26.71ab	459	2.0b	3.02b	25.0	509.6	2.4	5.96a	420.9	2.9	24.11	349.01
Chicken manure biochar	4.1	30.29b	402	2.1c	2.88b	26.8	476.2	2.5	7.58b	404.7	2.9	24.48	344.26
Level of significance	ns	$P < 0.03$	ns	$P = 0.002$	$P < 0.01$	ns	$P < 0.02$	ns	$P < 0.01$	ns	ns	ns	ns
Critical value[e]	3.0			1.8–1.9				2.3–2.7			3.0		

[a] Assuming that the flag leaf P levels are the same as the total whole shoot biomass.
[b] Values are means ($n = 32$).
[c] Means followed by the same letter in a column within the P main treatments or the amendment main treatments are not significantly different at $P < 0.05$.
[d] Not significant.
[e] Means equal to or less than the critical threshold value indicate marginal nutrient levels (Reuter and Robinson, 1997).

TABLE V

Soil chemical properties (0–10 cm) as affected by the P and organic amendment treatments measured at the end of the experiment in January 2013

Main treatment	pH in calcium chloride	NH_4	NO_3	P	K	S	Cu	Zn	Organic C	Cation exchange capacity
		mg kg^{-1}							g kg^{-1}	$cmol_+$ kg^{-1}
–P	4.79[a]	14.8	8.7	9.8	90	5.4	0.27	0.86	11.5	2.55
+P	4.83	14.6	8.2	13.1	101	5.6	0.28	1.04	11.1	2.60
Level of significance	ns[b]	ns	ns	$P < 0.001$	$P < 0.001$	ns	ns	$P < 0.01$	ns	ns
Control	4.80	14.0	8.0a[c]	10.9	91	5.2	0.25	0.96	11.3	2.58
Compost	4.81	15.8	9.1b	11.1	94	5.4	0.27	0.88	11.5	2.49
Wheat straw biochar	4.83	14.0	7.6a	11.6	105	5.9	0.31	0.97	11.2	2.62
Chicken manure biochar	4.80	15.0	9.0ab	12.0	93	5.5	0.27	0.98	11.1	2.61
Level of significance	ns	ns	$P < 0.05$	ns	ns	ns	ns	ns	ns	ns

[a] Values are means ($n = 32$).
[b] Not significant.
[c] Means followed by the same letter in a column within the P main treatments or the amendment main treatments are not significantly different at $P < 0.05$.

TABLE VI

Nutrient concentrations in tissues of the winter wheat and lupin crops and the summer forage sorghum crops[a)]

Main Treatment	Whole stems of sorghum in 2010–2011				Grains of lupin in 2011		Flag leaves of wheat in 2012					
	Ca	K	Mn	Cu	Mn	Zn	Ca	Mg	K	N	Fe	Cu
	g kg^{-1}		mg kg^{-1}				g kg^{-1}				mg kg^{-1}	
–P	5.0[b)]	17.8	50.7	5.75a[c)]	16.9a	22.6a	5.0a	2.5a	22.8a	42.4a	88.3a	3.4
+P	5.2	17.4	53.4	5.31b	16.5b	24.1b	5.3b	2.7b	23.8b	41.2b	99.4b	2.8
Level of significance	$P < 0.05$	ns[d)]	ns	$P < 0.01$	$P < 0.01$	$P < 0.02$	$P < 0.05$	$P < 0.01$	$P < 0.05$	$P < 0.01$	$P < 0.01$	$P < 0.01$
Control	5.2b	16.8a	55.7a	5.96a	16.7	22.4a	5.3	2.6a	22.9	41.8	93.9	3.2
Compost	5.3b	17.2ab	57.5a	5.92a	15.5	22.4a	5.3	2.7b	23.1	41.6	94.1	3.0
WS biochar	4.7a	18.9 b	46.6b	5.11b	19.1	24.6b	5.0	2.5a	23.6	41.8	92.6	3.1
CM biochar	5.2b	17.6ab	48.4b	5.14b	15.6	24.1b	5.1	2.5a	23.6	41.8	94.8	3.0
Level of significance	$P < 0.01$	$P < 0.05$	$P < 0.01$	$P < 0.01$	ns	$P < 0.05$	ns	$P < 0.05$	ns	ns	ns	ns
Critical value[e)]					8–10	19	1.8	2.0	20–25	35	25	2.5

[a)] Only where significant differences between the main treatments occurred are the data presented.
[b)] Values are means ($n = 32$).
[c)] Not significant.
[d)] Means followed by the same letter in a column within the P main treatments or the amendment main treatments are not significantly different at $P < 0.05$.
[e)] Means equal to or less than the critical value indicate marginal nutrient levels (Reuter and Robinson, 1997).

CM and WS biochars result in comparatively lower specific surface area, but retain more of their nutrients due to reduced volatilization (DeLuca *et al.*, 2009). The pH, organic C, P and N values for both biochars used in this study were within the ranges commonly found in pyrolysed grasses and poultry litter (Chan and Xu, 2009). Despite this, there are enormous variations in the chemical properties of biochars used in experiments. For instance, when compared with charred poultry litter (Singh *et al.*, 2010), the N, P and Zn values of the CM biochar ranged from being one quarter to five times higher, which may be explained by the differences in source of the poultry litter, pyrolysis temperature and analytical methods.

The increases in wheat grain yield for the biochars treatments (averaging 3% in the range of −1%–8%, $n = 4$) in this study were lower than the responses found in other parts of Western Australia where wheat yields increased on average by 9%, 10% and 12% (in the range from −9% to 30%, $n = 14$) at Moora, Pindar and Walkaway, respectively (Blackwell *et al.*, 2010; Solaiman *et al.*, 2010). When winter and summer crops were both considered, the average increase in yield associated with the biochar treatments in this study was 13% (in the range of −7%–32%, $n = 8$). Overall, the wheat yield increases are still modest compared to those in the international literature reviewed by Vaccari *et al.* (2011). In this study, P was the main limiting nutrient, whereas multiple nutrient limitations may be resolved using biochars which may further increase crop responses beyond those found in this study. The economic value of the organic amendments applied at rates of 5 t ha^{-1} ranged from 30 to 235 AUD ha^{-1} when calculated over the control over the three years of the experiment. The break even cost of applying biochar in this study ranged from 6 to 47 AUD t^{-1}.

Applications of P fertiliser resulted in significant yield increases for the wheat and lupin crops but not for the forage sorghum crops. These winter crop responses are not surprising given that soil P (Colwell P) values of 10–13 mg kg^{-1} within the 0–10 cm layer (Table V) range from being marginally deficient to adequate (Bell *et al.*, 2013). Phosphorus levels in wheat, lupin and sorghum plant tissues were marginal to adequate in the crops of each year (Reuter and Robinson, 1997). Due to the lack of response to P by the forage sorghum crops, we hypothesised that mycorrhizal colonisation of sorghum roots may have aided P uptake. The association between P uptake and mycorrhizal colonisation in sorghum is well documented (Jasper, 1979; Raju *et al.*, 1987; Treseder, 2004) as is the importance of mycorrhiza to plant nutrition in P-deficient soils (Mosse *et al.*, 1973). We also hypothesised that mycorrhiza would be more abundant where biochar was applied (Lehmann *et al.*, 2011). However, there was no difference in mycorrhizal colonisation in sorghum roots between the organically amended treatments and the control. The levels of colonisation measured in sorghum were low and were comparable with levels found in wheat at Pindar (Solaiman *et al.*, 2010). In other studies, up to 50%–80% mycorrhizal colonisation has been recorded on sorghum roots (Ellis *et al.*, 1992), compared to 30% in this study. Increased incidence of mycorrhiza would be expected given the low P status of the soils and drought stress (Ellis *et al.*, 1992).

The above results suggest that the increased sorghum yields in 2010–2011 occurred independently of mycorrhizal colonisation. The data also shows that the CM biochar increased yields of the non-mycorrhizal lupin plants (Trinick, 1977). Therefore, we conclude that a large part of the effect of the organic amendments was due to their nutrient content rather than to synergies with mycorrhiza. This assertion is supported by the reduced crop yield responses to the organic amendments over time. In this study, organic amendments had no significant impact on crop production after the third crop. In previous studies, increases in P use efficiency have been found where biochar has been applied (Blackwell *et al.*, 2010, Solaiman *et al.*, 2010). However, P use efficiency in the biochar and compost treatments was not higher than the control in all crops tested in this study.

The banded WS and CM biochars and the broadcast compost treatments at 5 t ha^{-1} could not be identified visually within the soil at the end of the experiment. Soil sampling within the banded treatment lines showed no differences in organic C or CEC which are key soil parameters that affect nutrient retention. Nitrate levels were significantly increased within the compost and CM biochar treatments. This is consistent with reductions in nitrate leaching found by Dempster *et al.* (2012) in biochar (25 t ha^{-1}) and clay-amended sands. Phosphorus levels within the soil were significantly increased by P additions to the crops. Where no P had been applied, P levels had dropped to levels ($<$ 10 mg P kg^{-1}) that are considered deficient in these soils (Bell *et al.*, 2013).

In this study, the biochar treatments did not result in significant improvements in soil properties that affect nutrient retention. None of the macro- or micronutrients measured in the biochar treatments were any higher than the control at the end of the experiment. Furthermore, there was no change in CEC as a result of the biochars being added at the rates used in this study. This is contrary to the findings of Dempster *et al.* (2012), who showed that biochar reduced ammonium and nitrate leaching in soil columns when applied at rates of 25 t ha^{-1}. Currently, clay is applied commercially to these sands to ameliorate water repellence. Added clay has been shown to increase nutrient retention in sands through increased CEC and organic C (Hall *et al.*, 2010) and reduced leaching of nutrients including ammonium, nitrate (Dempster *et al.*, 2012) and P (Mokhtari *et al.*, 2014).

CONCLUSIONS

Nutrient supply in biochars and compost could produce yield responses if the soil-available nutrient levels were limiting. In the sandplain soils studied, P was limiting and P supplied in biochars increased yield but only for 2 years, whereas annual P fertiliser addition increased yield in every year. During the experimental period, K and S were applied to each winter crop to avoid deficiencies; however, on the sandplain soils low in K or S, biochars had the potential to increase crop yields by alleviating these deficiencies. The amounts of K and S applied in the biochar exceeded crop requirements in the initial year. Enhanced mycorrhizal colonisation could not be demonstrated as a result of added biochar and compost. No differences in mycorrhizal colonisation or P uptake efficiency were found between the treatments. Furthermore, the yield response to the organic amendments was similar for the mycorrhizal (wheat and sorghum) and nonmycorrhizal (lupin) crop. The rates of biochar applied in this study were comparatively low. As a consequence, no change in soil nutrient retention was found between the treatments.

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