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Improving wheat production with deep banded Oil Mallee Charcoal in Western Australia

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SUMMARY

- There can be benefits to wheat income from deep banded oil mallee charcoal in the low rainfall areas of WA; the trials on acid sandy clay loam and acid sand in 2005 showed up to $96/ha additional gross income at wheat prices of $150/ha; especially when applied with mineral fertilisers and inoculated soil microbes. Much of the yield improvement can be explained by better grain survival, associated with reduced drought stress.

- There were encouraging effects of charcoal on arbuscular mycorrhiza (AM) colonisation. Banded oil mallee charcoal improved AM colonisation of wheat roots by 3 fold, when used with mineral fertilisers and AM is inoculated with the seed in the acid sandy clay loam with a low population of indigenous AM. Early phosphorus uptake was not improved by AM colonisation; P supply from the soil and applied fertiliser was already adequate.

- AM colonisation in spring was related to effects of charcoal application on grain survival in inoculated mineral fertiliser treatments. This infers AM hyphae may have improved water supply to reduce drought stress and loss of grains in these treatments.

- The true economic value of oil mallee charcoal will be clearer when the cost of charcoal production and application is better known and long term effects of charcoal, especially with inoculated AMs and mineral fertilisers is better understood. The potential to achieve a commercial return from the sequestration of charcoal as an offset for carbon dioxide emissions in broadscale agriculture will also help calculate true economic value.

- More research is worthwhile on the long term effects of incorporated charcoal in a range of soil conditions and seasons, from various sources and how low the banded charcoal rate needs to be to encourage better yields from mineral fertiliser with inoculated AM.

INTRODUCTION

Oil Mallees are the first native woody perennial species to be promoted as a commercial crop in the lower rainfall areas of the southwest land division of Western Australia, primarily stimulated by the need to ameliorate salinity caused by the clearing of native vegetation for agriculture (Bartle and Shea, 2002). Mallees are hardy plants that are well suited as a perennial crop through their ability to re-sprout from the large lignotuber after the above ground mass has been lost through fire or harvesting. In 2000 a group of Oil Mallee growers from Kalannie (300 km NE of Perth, Western Australia) began producing eucalyptus oil for the Australian market (see the Oil Mallee Association www.oilmallee.com.au). Integrated processing of mallee biomass to produce electricity, activated carbon and eucalyptus oil in a central processing facility has been the main emphasis of industry development since the late 1990's. Western Power, Enecon and the Oil Mallee Company have successfully developed a 'test of concept' Integrated Wood Processing (IWP) plant at Narrogin. Bell and Bennett (2002) estimated that the NPV of the net benefit to landowners of planting mallees in a local catchment area to supply a 5MW IWP would be about $6.2 million over 20 years. Charcoal is a valuable by-product of such IWPs and a possible by-product of farm based distillation of eucalyptus oil.

It has become well recognised in Japan and some other parts of Asia that charcoal from forestry products and rice hull can stimulate indigenous soil microbial activity (Ogawa, 1994; Nishio, 1996). Charcoal has especially encouraged arbuscular mycorrhiza (AM) which can help supply phosphorus symbiotically to many agricultural crops (Ogawa et al., 1983) and rhizobia, which can fix nitrogen from the atmosphere to supply leguminous plants (Nishio and Okano, 1991). Field experiments in Indonesia (Yamato et al. 2006) showed charcoal made from tree bark applied at 10 L/ha could increase the yield of maize by about 50%, to 15 t/ha, when added to 500 kg/ha of NPK (15:15:15) fertiliser on an acid highly weathered infertile tropical soil; associated with increased AM fungal colonisation. Lehmann and Rondon (2006) also identify numerous benefits of bio char to plant nutrition and microbial activity in the humid tropics. Benefits of charcoal to soil microbial activity have also been recognised in temperate forest environments (Zakrisson et al. 1996; Pietikainen et al. 2000).
Charcoal seems to assist microbial activity by having a porosity that provides a favourable microhabitat, weak alkalinity and by being a substrate unfavourable for saprophytes (Saito and Marumoto, 2002). AM fungi easily extend their extraradical hyphae into charcoal buried in the soil and sporulate in the particles (Ogawa, 1987). Postma et al. (1990) show evidence that rhizobia in pores <50 _m are protected from predation by protozoan predators; this could be an important microhabitat property provided by charcoal in soils with low clay content.

Encouragement and establishment of AM fungi in Western Australian soils has encountered many challenges. "The objective of identifying procedure for managing mycorrhizal fungi is more appropriately restated as managing conditions to suit the growth and activity of beneficial populations of mycorrhizal fungi" (Abbot and Gazey, 1994). Introduced AM fungi can suffer competition with indigenous AM fungi and be ineffective for crop phosphorus supply due to high levels of background soluble P (Gazey et al. 2004). Australian native grass species can also be much more efficient at accessing insoluble forms of phosphate than introduced wheat varieties; whose rhizosphere colonies can be very different (Marschner et al. 2006). This may be an adaptation to the low clay content environment of many Australian topsoils; low clay content reduces the amount of small pore space to help some micro-organisms prosper. Charcoal in suitable amount and form may provide the missing microhabitat in WA topsoils to help introduced AM fungi and other microbes survive and colonise introduced agricultural crops.

One commercial fertiliser company (Western Mineral Fertilisers; Tenterden WA) has developed products which minimise the abundance of readily soluble phosphorus to encourage symbiotic and other processes of inoculated soil microbes. Zeolite was initially included and intended to provide enhanced ion exchange capacity, and also a micro habitat within the zeolite pores; however the pore volume may not be sufficient. It was a reasonable hypothesis that charcoal addition may improve the microhabitat further than the use of zeolite.

The opportunity to test hypotheses about charcoal effects on soil and use of soil microbes to improve crop nutrient supply came about in 2005. There was an intensive research effort to examine the efficacy of very wide rows of wheat on shallow soils in the low rainfall areas east of Geraldton (Blackwell et al. 2006; Blackwell 2007). With some support and encouragement from the Oil Mallee Company and Western Mineral fertilisers we developed the following experiments using no-till methods for crop establishment and very wide rows to minimise drought stress. Attempts to follow the long-term effects at Pindar failed due to a very dry winter season in 2006.

MATERIALS and METHODS

The details of the soil conditions, agronomy and rainfall are shown in table1.

Table 1. Trial sites, agronomy, rainfall and soil conditions for the field experiments.

	Site 1	Site 2	Site 3
Reference in text	PINDAR	KALANNIE 1	KALANIE 2
Property	Marlingu Farms, Pindar M&D Kerkmans.	"Bungadale" farm, Ian and Robyn Stanley, Kalannie.	
Soil type	Shallow weak sandy clay loam; about 20% clay mainly kaolin	Pale yellow sand	
Depth to rock, mm	380	> 1m	
Soil chemistry	P 40 ppm, available (Colwell),K 140 ppm available (Colwell),1.55 % OM, pH 5.3 (H_2O) Ex. Al 0.6 ppm CEC 1.8 meq/100g	P 44 ppm, available (Colwell)K 108 ppm available (Colwell),1.02 % OM, pH 5.3 (H_2O)	
Sowing date	20th May	14th June	14th June
Seeding rate of wheat	60 kg/ha graded to 2.5mm sieve on 600mm row spacing; variety Bonnie Rock.	70 kg/ha of variety Wyalkatchem	
		600 mm row spacing seed and fertiliser	300 mm row spacing
Fertiliser (kg/ha) (PINDAR)	55 kg/ha or 30 kg/ha of 'MultiMAPS' ® compound soluble fertiliser (United Farmers Cooperative Perth;% N 8: P 17.6: S 7: Ca 8.6: Cu 0.5: Zn 0.5); or 100 kg/ha of compound mineral fertiliser (Western Minerals Fertilisers Ltd, Tenterden, WA %N 5.5: P 7: K 5: S 8: Ca 7: Mg 1.7: + trace elements) with microbes coated on the seed at sowing; 10 kg/ha of manganese sulphate added to all fertiliser; the site was deficient in manganese. Deep banded with a DBS opener; always applied on 300mm rows (50% of fertiliser deep banded on the inter-row of the 600mm plant row spacing). 40 kg/ha of 'Nitrogold'® (%N 26: %S14) top dressed 5th July.		
Microbe Seed Inoculum (PINDAR)	WMF Ag Blend beneficial microbes (@ 750g/tonne seed equivalent) which included several non-pathogenic fungi and bacteria such as *Glomus intraradices, Ascomycete*, *Azospirillum, Azotobacter, Bacilli*, *Cellulomonas, , Pseudomonas, Streptomyces, Saccharomyces.*		
Fertiliser (kg/ha) (KALANNIE)	'MAPZC'® (Summit Fertilisers; %N 10.6: P 21: S 8: Cu 0.3: Zn 0.3: Mn 0.02: 9 ppm Mo) at 110 kg/ha to both sites; Flexi-N at 50L/ha to site 2 only.		
Paddock rotation	(Pindar) 2004 Pasture, ploughed after a September rain. (Kalannie) pasture.		
Herbicides (PINDAR)	Early and late knockdowns with glyphosate and summer broadleaf herbicide (1L/ha glyphosate and 3g/ha 'Ally'®) 8th July. Broadleaf control with 'Riddler'® (300ml/ha) and 'Ally'® (3g/ha) 8th June. 300ml of fungicide 'Tilt'® applied 28th June as insurance against leaf rust.		
Herbicides (KALANNIE)	'Achieve'® 250 g/ha; 'Hoegrass'® 220 ml/ha;'Giant'® 350 ml/ha; MCPA 0.3 L/ha		
Growing Season Rainfall (PINDAR)	May to October 190 mm (total 255); 20mm of irrigation applied to 4.3x2.4m sub plots 5th August. March, 52 April, 11 May, 57 June, 46 July, 7 August, 53 September, 23 October, 6.		
Growing Season Rainfall (KALANNIE)	May to October 191 mm (total 249); March, 38 April, 17 May, 47 June, 61 July, 13 August, 42 September, 24 October, 4.		

Charcoal preparation

Oil mallee charcoal was made from biomass remaining after extraction of Eucalyptus oil. The oil was extracted by a steam distillation unit from leaves, branches and stems of mallee trees harvested from plantings at Kalannie. The biomass was partly pyrolysed to charcoal by an open pan "Moki" method. The partly pyrolysed biomass was crushed under the wheels of a small tractor (Massey Ferguson 165) and sieved to <2-3mm to remove the unpyrolysed wood. The composition of the resulting oil mallee charcoal was; pH ($CaCl_2$) 8.4, conductivity 25 _S/m; surface area 81 m^2/g; by CO_2 gas adsorption at 150°C for 10 h. Fixed Carbon 30.4 % dry weight and 22.5% wet weight, ash 53.7% and volatile substances 16% (dry basis; by JIS M 8812), N 1.2%, P 0.12%, K 0.7%, S 0.12%, Ca 2.8%, Na 6450 ppm, Mn 1340 ppm, Cu 8 ppm, Zn 38 ppm and CEC 59 meq/100g.

Charcoal placement

At both locations the prepared oil mallee charcoal was placed at 50-200mm depth over a width of 100 mm on 600 or 300 mm row spacing with a plot air seeder using a knife point and presswheel system (DBS technology of Ausplow Ltd). The placement was into moist soil in the first week of April at Pindar and in the second week of June at Kalannie. Each pass of the seeder could apply 1.5 t/ha of charcoal on 600 mm row spacing and 100mm row width, thus 4 passes were needed to apply 6 t/ha. Controls were established to test the effect of cultivation without charcoal. The charcoal at sites 1 and 2 was 7% moisture w/w; the charcoal at site 3 was 26% moisture w/w.

Treatments and Experimental design.

The treatments in the field experiments (table 2) were laid out in randomized block designs with three or four replicates. Plots were 2.5 m wide with 2 measured rows and 2 guard rows, for 600mm rows, plot length was 30m.

Table 2. Treatments at each site; MC = Mallee charcoal. Rates are in bands 100 mm wide. min fert = Western Minerals fertiliser and microbes, sol fert = soluble fertiliser (United Farmers Multi MAPS; Pindar. MAPZC; Kalannie)

Pindar 600mm rows	**Kalannie 1** 600mm rows	**Kalannie 2** 300mm rows
1. One pass no MC& 100 kg/ha min fert	**1.** One pass no MC& 110 kg/ha sol. fert	**1.** One pass no MC& 110 kg/ha sol. fert
2. 4 passes on MC & 100 kg/ha min fert	**2.** 4 passes on MC & 110 kg/ha sol. fert	**2.** 4 passes on MC & 110 kg/ha sol. fert
3. One pass no MC& 30 kg/ha sol. fert	**3.** 1.5 t/ha MC & 110 kg/ha sol. fert	**3.** 6.0 t/ha MC & 110 kg/ha sol. fert
4. 4 passes on MC & 30 kg/ha sol. fert	**4.** 3.0 t/ha MC & 110 kg/ha sol. fert	
5. One pass no MC& 55 kg/ha sol. fert	**5.** 6.0 t/ha MC & 110 kg/ha sol. fert	
6. 4 passes on MC & 55 kg/ha sol. fert		
7. 1.5 t/ha MC & 100 kg/ha min fert		
8. 3.0 t/ha MC & 100 kg/ha min fert		
9. 6.0 t/ha MC & 100 kg/ha min fert		
10. 1.5 t/ha MC& 30 kg/ha sol. fert		
11. 3.0 t/ha MC& 30 kg/ha sol. fert		
12. 6.0 t/ha MC& 30 kg/ha sol. fert		
13. 1.5 t/ha MC& 55 kg/ha sol. fert		
14. 3.0 t/ha MC &55 kg/ha sol. fert		
15. 6.0 t/ha MC &55 kg/ha sol. fert		

Measurements; these were the methods used at Pindar and Kalannie, unless stated otherwise.

Crop establishment, tillering, nutrient uptake and soil chemistry

Crop establishment was measured by counting plants on one metre row length, six counts per plot on 5th June. Tiller numbers, tiller biomass and nutrient content were measured on 4th July at Pindar (before nitrogen fertiliser was top dressed) and 28th July at Kalannie from four 300 mm lengths of row from each plot; bulked together for measurement. Nutrient uptake was calculated as the product of crop dry matter and leaf nutrient concentration. Soil pH (in water), EC and organic matter content and soil fertility at tillering were measured samples from 0-10 cm depth at the same 'in row' locations as the crop tiller samples.

Root colonisation (Pindar only)

Four replicate soil cores with roots of plants were randomly collected from the middle two rows of the three replicate plots of treatments with 0, 3 and 6 t/ha of charcoal applied to each of the fertiliser treatments; treatments 2,4,6, 8, 9, 11, 12, 14 and 15 in table 2. This was done on 30th June and from both the watered sub plots and the water-stressed rows on 14th September. The samples were stored in zip-lock plastic bags. Roots were carefully washed free of soil and organic debris. Approximately 300mg of Roots attached to the base of each plant were sub-sampled (ie any loose roots were not included).

Root staining and AM scoring

The sub-samples were cleared in 3mls 10% (w/v) KOH for 6 hours @ 80°C, in 10ml glass beakers covered with aluminium foil to prevent evaporation. Cleared roots were collected on a fine sieve and rinsed with DI water. Cleared roots were stained in 3mls 0.03% (w/v) Chlorazol Black E in a lactoglycerol solution (1:1:1 lactic acid, glycerol and water) for 2 hours @ 80°C, in glass beakers covered with aluminium foil to prevent evaporation (Brundrett et al. 1984). Stained roots stained were stored in 50% glycerol. Root lengths were determined using an Olympus stereo dissecting microscope. The proportion (%) of the root length colonised by mycorrhizal infections were determined with the gridline intercept method (Giovannetti and Mosse 1980) by randomly dispersing the stained roots in a 9-cm diameter Petri plate with gridlines. Root colonisation by AM fungi was defined by the presence of arbuscules within roots and expressed as percentage of root length; six repeated measurements were taken on each sample, redispersing the sample between each measurement. The results of all six measurements were combined to derive a total measurement of root length and percentage colonisation for each of the four roots sampled from each treatment. Each root sample was also examined separately by making slides and viewing them with a compound microscope (McGonigle et al. 1990) to confirm adequate clearing, staining and mycorrhizal presence or absence.

Crop yield and components of yield

Biomass, head number, grain yield, grain weight and grain quality were measured from the whole irrigated sub plots at Pindar. Mature crop came from two 2.4 m long rows; oven dry weight, number of filled and unfilled heads and grain yield as total grain weight at 12% moisture content were measured, as well as grain quality measurements of size (<2 mm sieve 'screenings' and 2-2.5 mm sieve 'small grain') and grain protein. At Kalannie grain yield was also measured with a small plot harvester.

Statistical analysis

The data was evaluated for least significant differences (lsd) between treatments with analysis of variance using Genstat (v.8). Missing plots for some data were estimated by 'missing value' estimations in the procedure. Restricted space for the field experiment did not allow all the intended factorial combinations of treatments; two pass controls for the 3t/ha rate of charcoal were excluded and effects later interpolated. Charcoal application before seeding encountered some technical problems and 2 more plots in the experiment were lost.

RESULTS

Pindar.

Table 3. PINDAR: Soil fertility (0-10 cm depth) in the crop row during tillering. Values significantly different from no charcoal application at P<0.05 are shown bold.

Fertiliser and rate	Charcoal rate, t/ha in row	pH (H_2O)	OM %	CEC meq/ 100g	ex. K %	ex. Ca %	ex. Mg %	ex. Na %
Soluble	0 (1 pass)	4.7	1.32	1.7	15.5	55.2	15.8	13.4
55 kg/ha	0 (4 passes)	4.8	1.26	1.9	13.5	55.3	17.6	13.6
	1.5	4.8	1.32	**2.1**	**11.9**	57.9	15.6	14.5
	3	4.8	1.39	1.9	13.4	55.5	16.8	14.3
	6	4.8	**1.56**	1.8	13.7	58.5	14.6	13.1
Soluble	0 (1 pass)	4.7	1.32	1.8	17.2	59.7	13.5	9.9
30 kg/ha	0 (4 passes)	4.8	1.28	1.9	15.0	59.8	15.0	10.1
	1.5	4.9	1.28	2.1	**14.3**	56.5	**16.3**	12.9
	3	4.8	1.28	1.8	14.3	55.1	**16.3**	**14.2**
	6	**5.0**	1.45	**2.2**	13.8	60.6	15.2	10.4
Mineral	0 (1 pass)	4.8	1.29	1.6	18.7	56.6	14.2	11.3
100 kg/ha	0 (4 passes)	4.8	1.27	1.7	16.2	56.6	15.8	11.3
+ microbes	1.5	4.8	1.30	1.8	**12.1**	58.0	15.6	14.3
	3	4.8	1.21	**2.0**	**14.0**	55.7	**17.1**	13.2
	6	4.9	1.40	**2.0**	**14.3**	58.3	15.8	11.7
lsd(P<0.05)	Fertiliser	0.08	0.12	0.16	1.15	2.43	0.75	1.66
lsd(P<0.05)	Charcoal	0.10	0.15	0.20	1.47	3.13	0.96	2.14
lsd(P<0.05)	Char x Fert.	0.17	0.26	0.35	2.57	5.42	1.67	3.71

Charcoal had little effect on pH except for a significant increase of 0.2 pH units at the 6t/ha rate with low rates of soluble fertiliser. Soil organic matter tended to increase with the rate of applied charcoal; but there is much variability in the data, exacerbated by inadequate sampling frequency. Cation exchange capacity was increased with charcoal rates; but with the higher level of soluble fertiliser, there was a reverse effect. Charcoal tended to decrease the exchangeable K with the mineral fertiliser. Exchangeable Mg and Na could to increase with charcoal for low rates of soluble fertiliser and mineral fertiliser.

Table 4. PINDAR: Plant density on 5th June and density and biomass on 4th July; before application of nitrogen fertiliser. Values significantly different from no charcoal application at $P<0.05$ are shown bold. Plants were counted in early June and tillers sampled in early July.

Fertiliser and rate	Charcoal rate, t/ha in row	plant /m^2 June	plant/m^2 at tillering	tillers /m^2	June visible biomass (rating)	tillering biomass g/m^2
Soluble	0 (1 pass)	126	124	149	5.8	24.1
55 kg/ha	0 (4 passes)	141	145	166	5.7	21.4
	1.5	125	**162**	**198**	5.8	26.7
	3	133	138	168	5.7	24.3
	6	136	140	131	6.0	**16.9**
Soluble	0 (1 pass)	90	90	128	5.0	18.2
30 kg/ha	0 (4 passes)	100	102	147	4.8	16.7
	1.5	**127**	**130**	131	**5.3**	**17.7**
	3	**129**	**150**	162	**5.5**	**22.5**
	6	122	139	155	**6.1**	**25.6**
Mineral	0 (1 pass)	72	80	110	5.2	17.7
100 kg/ha	0 (4 passes)	80	94	121	5.0	15.6
+ microbes	1.5	74	95	140	**4.2**	15.4
	3	73	87	111	4.5	17.7
	6	89	104	144	5.3	18.7
lsd($P<0.05$)	Fertiliser	10.4	17.3	21.1	0.29	2.55
lsd($P<0.05$)	Charcoal	13.4	22.3	27.3	0.37	3.29
Lsd($P<0.05$)	Char x Fert.	23.2	38.6	47.2	0.65	5.69

Plant establishment was poor for the mineral fertiliser because the seed dressing of inoculum suspension wetted the seed and slowed the flow of seed from the combine. Charcoal at the highest rate reduced tillering biomass and tiller density for crop with the high rate of soluble fertiliser. Charcoal improved plant establishment and tillering biomass with the low rate of soluble fertiliser. Charcoal had no effect on establishment or tillering biomass with the mineral fertiliser.

Table 5a.PINDAR: Nutrient Uptake by wheat tillers. Values significantly different from no charcoal application at $P<0.05$ are shown bold. Plants sampled on 4th July.

Fertiliser and rate	Charcoal rate, t/ha in row	tillering biomass g/m^2	N uptake g/m^2	P uptake g/m^2	K uptake g/m^2	Mn uptake g/m^2	Cu uptake mg/m^2	S uptake mg/m^2	Na uptake mg/m^2	Zn uptake mg/m^2
Soluble	0 (1 pass)	24.1	95	8.2	104	7.8	159	7.1	1.81	744
55 kg/ha	0 (4 passes)	21.4	84	6.8	92	6.2	142	6.3	1.60	623
	1.5	26.7	105	9.4	114	8.0	176	7.8	1.95	786
	3	24.3	93	8.1	104	6.2	159	6.9	1.65	757
	6	**16.9**	64	5.2	69	5.6	101	**4.9**	**1.27**	**454**
Soluble	0 (1 pass)	18.2	75	6.0	79	4.8	114	5.4	1.12	542
30 kg/ha	0 (4 passes)	16.7	68	5.2	72	3.8	108	4.9	1.01	468
	1.5	**17.7**	69	5.9	79	4.5	128	5.3	1.17	525
	3	**22.5**	90	6.8	95	**5.8**	150	6.5	1.42	687
	6	**25.6**	**103**	**8.4**	**114**	**6.1**	**174**	7.4	**1.61**	**739**
Mineral	0 (1 pass)	17.7	75	6.0	74	5.3	115	5.6	1.23	579
100 kg/ha	0 (4 passes)	15.6	66	4.9	65	4.2	102	4.9	1.09	483
+ microbes	1.5	15.4	66	5.0	68	4.3	98	4.8	1.08	465
	3	17.7	72	5.7	76	5.0	118	5.3	1.19	509
	6	18.7	78	5.7	79	4.9	116	5.6	1.25	506
lsd $P<0.05$	Fertiliser	2.55	10.9	0.85	12.6	0.65	21.6	0.76	0.176	93
lsd $P<0.05$	Charcoal	3.29	14.0	1.10	16.2	0.83	27.9	0.99	0.227	120
lsd $P<0.05$	Char x Fert.	5.69	24.3	1.90	28.1	1.44	48.4	1.71	0.394	208

At 55 kg/ha of soluble fertiliser the highest rate of charcoal decreased uptake of Zn, Na and S. This was due to less tiller biomass, rather than tissue concentration; see table 5b. At 30 kg/ha of soluble fertiliser the highest rate of charcoal (6 t/ha) increased uptake of all elements. This was associated with a high tiller biomass, but not significantly higher than the 3 t/ha rate; thus trends of tissue concentration increase between the 3 and 6 t/ha charcoal rates explain some of the increased nutrient uptakes for the 6 t/ha charcoal rate. The available nutrients in the charcoal (table 5b) may explain some of the uptake improvements seen for this treatment. For the mineral fertiliser and inoculated microbes there was no significant effect of charcoal on uptake of any nutrients in the young leaves of the crop.

Table 5b. PINDAR: Nutrient concentration in young leaves. Values significantly different from no charcoal application at P<0.05 are shown bold. *Significant reductions by fertiliser treatment are shown in bold italics.*

Fertiliser and rate	Charcoal rate, t/ha	N %	P %	K %	Mn ppm	Cu ppm	S %	Na ppm	Zn ppm
Concentration in charcoal		**0.91**	**0.12**	**0.66**	**1340**	**8**	**0.12**	**6450**	**38**
Range of approx. lower limit		**3.5- 4.0**	**2 – 2.5**	**2.5 - 3.5**	**12**	**2**	**0.25 – 0.35**		**20**
Soluble	0 (1 pass)	***3.93***	0.340	4.3	328	6.5	***0.30***	75	31
55 kg/ha	0 (4 passes)	***3.93***	0.317	4.3	293	6.7	***0.30***	75	29
	1.5	***3.93***	0.353	4.3	298	6.7	***0.29***	73	29
	3	***3.80***	0.335	4.3	258	6.5	***0.29***	68	31
	6	***3.77***	0.307	4.1	333	6.0	***0.29***	75	27
Soluble	0 (1 pass)	4.10	0.329	4.3	275	6.3	***0.30***	*62*	29
30 kg/ha	0 (4 passes)	4.10	0.307	4.3	258	6.5	***0.30***	*62*	27
	1.5	3.90	0.332	4.4	256	7.0	***0.30***	*65*	29
	3	4.00	0.300	4.2	257	6.7	***0.29***	*63*	30
	6	4.03	0.327	4.5	244	6.9	***0.29***	*63*	29
Mineral	0 (1 pass)	4.27	0.338	4.2	306	6.3	0.31	70	33
100 kg/ha	0 (4 passes)	4.27	0.315	4.2	270	6.5	0.31	70	31
+ microbes	1.5	4.30	0.327	4.4	282	6.5	0.31	70	30
	3	4.07	0.320	4.3	282	6.7	0.30	67	29
	6	4.20	0.305	4.2	262	6.2	0.30	68	27
lsd P<0.05	Fertiliser	0.12	0.010	0.17	37	0.38	0.012	6	2.0
lsd P<0.05	Charcoal	0.15	0.013	0.22	48	0.49	0.016	7	2.6
lsd P<0.05	Char x Fert.	0.26	0.022	0.38	83	0.85	0.027	13	4.5

The N concentrations were generally more marginal for the higher rate of soluble fertiliser than the other fertiliser treatments. The S concentrations were generally more marginal for the soluble fertiliser treatments than the mineral fertiliser treatments. Manganese was in luxury supply due to the extra Mn fertiliser added to compensate for soil deficiency. There was no clear inadequacy for plant growth for any of the nutrients measured in the crop tissue in any of the treatments.

Table 6. PINDAR: Root colonization by arbuscular mycorrhiza (AM). The average percentage of the root length occupied by mycorrhizal infections: Irrigated = subplots which had 20 mm irrigation in August. Values significantly different from nil charcoal are shown in bold.

Sampling time		June	Sept irrigated	Sept un-Irrigated
Fertiliser and rate	Charcoal rate, t/ha in row	Root length colonised %	Root length colonised %	Root length colonised %
Soluble	0 (4 passes)	0	2	0
55 kg/ha	3	1	6	5
	6	9	13	3
Soluble	0 (4 passes)	0	1	0
30 kg/ha	3	6	17	3
	6	7	22	3
Mineral	0 (4 passes)	24	15	32
100 kg/ha	3	12	**46**	23
+ microbes	6	**47**	**45**	**62**
lsd P<0.05	Fertiliser	13.3	14.0	8.3
lsd P<0.05	Charcoal	13.3	14.0	8.3
lsd P<0.05	Char x Fert.	23.0	24.3	14.4

AM root colonisation was significantly higher in AM-inoculated than in non-inoculated plants. Inoculated plants had higher average proportion (%) of mycorrhizal associations in the higher charcoal treatments; especially in the un-irrigated samples in September. The colonisation of the un-irrigated highest charcoal treatment was also noticeably high. Non-inoculated plants growing with soluble fertilisers consistently remained low or non-mycorrhizal. The highest proportion of colonisation in the non-inoculated plants occurred in the samples from irrigated plots in September with the lower rate of soluble fertiliser and the highest rate of applied charcoal. Root system size was not measured, but the visual impression was of a larger root system of the plants grown with mineral fertiliser, compared to those grown with soluble fertiliser. This would lead to even greater differences between fertiliser treatments if the total amount of root colonisation had been measured.

Table 7. PINDAR: Crop yield and components of yield. Values significantly different from no charcoal application at P<0.05 are bold

Fertiliser and rate	Charcoal rate, t/ha in row	yield, kg/ha	Scree nings %	Small grain %	Heads /m^2	grains/ head	grain wt mg	grain protein %
Soluble	0 (1 pass)	1792	2.8	22	172	25.7	41	13.5
55 kg/ha	0 (4 passes)	1872	3.1	14	185	24.3	42	13.1
	1.5	1787	2.1	17	197	20.8	**45**	13.2
	3	1889	1.9	15	191	24.7	40	13.0
	6	1809	2.2	21	199	20.9	43	**14.0**
Soluble	0 (1 pass)	1875	1.6	48	151	33.4	41	12.9
30 kg/ha	0 (4 passes)	1961	1.9	26	156	30.4	42	13.4
	1.5	1885	2.1	**16**	165	26.7	43	12.9
	3	1788	3.0	18	188	23.6	40	13.7
	6	**2305**	2.0	19	178	30.8	42	13.1
Mineral	0 (1 pass)	1350	3.0	29	160	21.3	40	12.9
100 kg/ha	0 (4 passes)	1408	3.0	16	174	20.2	41	13.7
+ microbes	1.5	**2032**	2.0	18	154	**29.6**	**45**	13.3
	3	**2018**	2.1	20	161	**28.2**	**45**	13.6
	6	**2010**	2.8	16	161	**29.4**	43	13.1
lsd (P<0.05)	Fertiliser	80	0.65	9.5	18.1	3.31	2	0.39
lsd (P<0.05)	Charcoal	103	0.83	12.3	23.4	4.27	3	0.50
lsd (P<0.05)	Char x Fert.	178	1.44	21.3	40.5	7.39	4	0.87

Charcoal banded at 6 t/ha with 30 kg/ha of soluble fertiliser improved yield over no charcoal by about 340 kg/ha (18%). There was no clear single yield component associated with this yield increase. Any charcoal banded with the Mineral fertiliser improved grain yield by about 640 kg/ha (46%). This was mainly associated with improved number of grains per head and secondarily with grain weight. There was no effect of charcoal rate on yield or grain size for the higher rate of soluble fertiliser. Grain protein was relatively high and typical for seasons affected by drought stress; but influenced little by treatment. The 6 t/ha rate of charcoal with the higher rate of soluble fertiliser enabled a 0.9% increase of grain protein.

KALANNIE

The results from trials Kalannie 1. and Kalannie 2. are presented together.

Table 8. KALANNIE 1: 600 mm rows. Soil properties. Values significantly different from no charcoal application at P<0.05 are bold.

Charcoal rate, t/ha in row	pH H$_2$0	Organic matter %	P mg/kg	K mg/kg	S mg/kg	ex K %	ex Ca %	ex Na %
0 (1 pass)	5.50	1.14	125	101	11.2	0.25	1.58	0.11
0 (4 passes)	5.53	1.19	124	96	10.4	0.25	1.49	0.11
1.5	5.52	1.11	134	83	11.6	0.21	1.49	0.12
3	5.50	1.14	116	94	11.4	0.23	1.47	0.12
6	5.57	1.02	120	95	10.2	0.23	1.41	0.10
lsd <0.05	0.09	0.17	35.8	24.2	2.26	0.05	0.132	0.022

Charcoal rate had no significant effect on pH, organic carbon, available P, N or S, exchangeable K or Na. The sampling errors were too high.

Table 9. KALANNIE 2: 300 mm rows Soil properties. Values significantly different from no charcoal application at P<0.05 are bold.

Charcoal rate, t/ha in row	pH H$_2$0	Organic matter %	P mg/kg	K mg/kg	S mg/kg	ex K %	ex Ca %	ex Na %
0 (1 pass)	5.56	1.05	80.9	95.0	12.5	0.226	1.70	0.085
0 (4 passes)	5.70	1.19	66.6	85.6	8.9	0.209	1.81	0.083
3#	5.67	1.17	57.3	81.7	9.3	0.208	1.66	**0.098**
lsd	0.163	0.192	37.53	11.07	6.29	0.0172	0.497	0.0057

rate approx. 50% of 6t/ha due to double row spacing and high moisture content The charcoal at sites 1 & 2 was 7% moisture w/w; the charcoal at site 3 was 44%.

Charcoal application has increased the exchangeable sodium, but the variation in the data is too large to identify any other effects of charcoal addition.

Table 10. KALANNIE 1: 600 mm rows. Crop establishment and early growth; with uptake of major nutrients. Values significantly different from no charcoal application at P<0.05 are shown bold. Plants were counted and tillers sampled in late July.

Charcoal rate, t/ha in row	pl/m^2	till/m^2	tiller biomas g/m^2	N uptake g/m^2	P uptake g/m^2	K uptake g/m^2
0 (1 pass)	91	111	11.3	0.60	0.095	0.39
0 (4 passes)	93	109	10.9	0.60	0.089	0.37
1.5	91	**135**	**13.6**	**0.74**	0.118	**0.48**
3	88	129	12.3	0.62	0.098	0.47
6	87	120	11.1	0.62	0.092	0.42
lsd	17.3	14.6	1.40	0.144	.334	0.643

Low rates of charcoal increased tiller density by 25 and tiller dry wt by 2.3 g/m^2. This was associated with more N, K and possibly P uptake; all driven by tiller biomass differences, tissue concentrations were similar. Tiller number and dry matter and N, P and K uptake declined with increasing banded charcoal rate; this was a negative effect on growth by incorporated charcoal. N and P uptake was very low because tiller biomass was low.

Table 11. KALANNIE 1: 600 mm rows. Uptake of other nutrients. Values significantly different from no charcoal at $P<0.05$ are bold.

Charcoal rate, t/ha in row	Zn uptake mg/m^2	B uptake mg/m^2	Ca uptake mg/m^2	Cl uptake mg/m^2	Cu uptake mg/m^2	Fe uptake mg/m^2	Mg uptake mg/m^2	Mn uptake mg/m^2
0 (1 pass)	0.32	0.039	35.9	175	0.07	3.64	16.3	1.30
0 (4 passes)	0.29	0.040	34.1	172	0.07	3.37	15.2	1.30
1.5	**0.40**	0.052	**46.8**	**245**	**0.10**	4.47	**20.6**	1.57
3	**0.40**	0.053	44.3	220	0.09	3.77	18.2	1.83
6	**0.34**	0.044	35.6	197	0.07	3.08	15.3	1.36
lsd	0.030	0.016	7.25	34.2	0.015	0.83	2.89	0.371

The nutrient uptake behaviour of all these elements showed the same pattern as for N P and K. Zinc uptake seemed to be most improved by charcoal

Table 12. KALANNIE 2: 300 mm rows. Crop establishment and early growth; with uptake of major nutrients. Values significantly different from no charcoal application at $P<0.05$ are shown bold. Plants were counted and tillers sampled in late July. Brackets indicate P approx = 0.1

Charcoal rate, t/ha in row	pl/m^2	till/m^2	tillering biomass g/m^2	N uptake g/m^2	P uptake g/m^2	K uptake g/m^2	S uptake g/m^2	Cu uptake mg/m^2
0 (1 pass)	51.1	88.9	7.19	0.36	0.040	0.25	2.54	43
0 (4 passes)	61.3	103.1	8.37	0.39	0.047	0.31	2.87	50
3#	(72.7)	(116.6)	(9.65)	0.45	0.054	0.34	3.24	56
lsd	14.52	17.62	1.696	0.115	0.019	0.111	0.666	11.6

see note about higher water content in table 9.

There were no improvements to uptake of macronutrients and copper by incorporation of charcoal. There may have been an improvement in early growth.

Table 13. KALANNIE 2: 300 mm rows. Uptake of other nutrients. Values significantly different from no charcoal application at $P<0.05$ are bold. Brackets indicate P approx = 0.1.

Charcoal rate, t/ha in row	Zn uptake mg/m^2	B uptake mg/m^2	Ca uptake mg/m^2	Na uptake mg/m^2	Cl uptake mg/m^2	Fe uptake mg/m^2	Mg uptake g/m^2	Mn uptake mg/m^2
0 (1 pass)	195.1	22.4	3.57	0.29	13.0	2596	1.21	1248
0 (4 passes)	220.1	27.8	4.12	0.35	15.3	3102	1.37	1360
3#	(274.7)	31.4	4.58	0.48	(18.8)	3392	1.65	(1688)
lsd	59.7	6.38	0.833	0.117	3.79	807	0.359	256

see note about higher water content in table 9.

There were no improvements to uptake of micronutrients by incorporation of charcoal.

Table 14. KALANNIE 1: 600 mm rows. Wheat yield and components of yield. Values significantly different from no charcoal application at P<0.05 are bold

Charcoal rate, t/ha in row	yield, kg/ha	Protein %	Screenings % <2mm	hl wt g	small grain % 2-2.5mm	grain wt. mg	heads /m^2
0 (1 pass)	872	11.9	8.9	78.28	58	35.3	137
0 (4 passes)	867	12.1	9.1	77.87	57	35.9	139
1.5	**929**	12.4	**11.0**	76.97	59	35.6	144
3	**925**	11.8	9.7	77.83	47	35.0	159
6	**943**	12.1	9.0	77.84	54	36.1	153
lsd(P<0.05)	35.4	0.95	3.78	1.445	11.7	3.20	28.8

There were yield increases of 57 kg/ha for 1.5 t/ha of charcoal and 76 kg/ha for 6 t/ha of charcoal. Increasing charcoal rate had no effect on grain protein. Low rates of charcoal increased screenings. The yield increases by charcoal application could not be associated with any of the components of yield.

Table 15. KALANNIE 2: 300 mm rows. Wheat yield and components of yield. Values significantly different from no charcoal application at P<0.05 are bold. Brackets indicate P approx = 0.1

Charcoal rate, t/ha in row	yield, kg/ha	Protein %	Screenings % <2mm	hl wt g	small grain % 2-2.5mm	grain wt. mg	heads /m^2
0 (1 pass)	883	11.9	7.21	78.09	53	37.5	143
0 (5 passes)	875	12.1	7.09	78.52	46	35.5	140
3 #	(958)	11.6	6.66	78.72	48	36.6	162
Lsd p<0.05	87.5	1.06	1.729	1.306	21.9	3.53	36

see note about higher water content in table 9.

There was no significant yield increase by charcoal addition in this experiment at P<0.05.

6. Discussion

1. Influence of charcoal on grain yield

The grain yields were calculated as the net effect of charcoal addition. The net yield for each charcoal treatment was the yield with charcoal after subtraction of the yield with the same cultivation and no charcoal and added to the mean yield with no charcoal. The yield without charcoal for the 3 t/ha rate (two passes) had to be interpolated from the yields for one pass and the yield for four passes without charcoal.

The mean yield without charcoal was derived from the mean values of the yield with one pass and four passes. These adjustments were generally small in comparison to the larger effects of charcoal addition, but gave more precision in the interpretation.

Effects for soluble fertilisers at normal rates; Pindar and Kalannie.

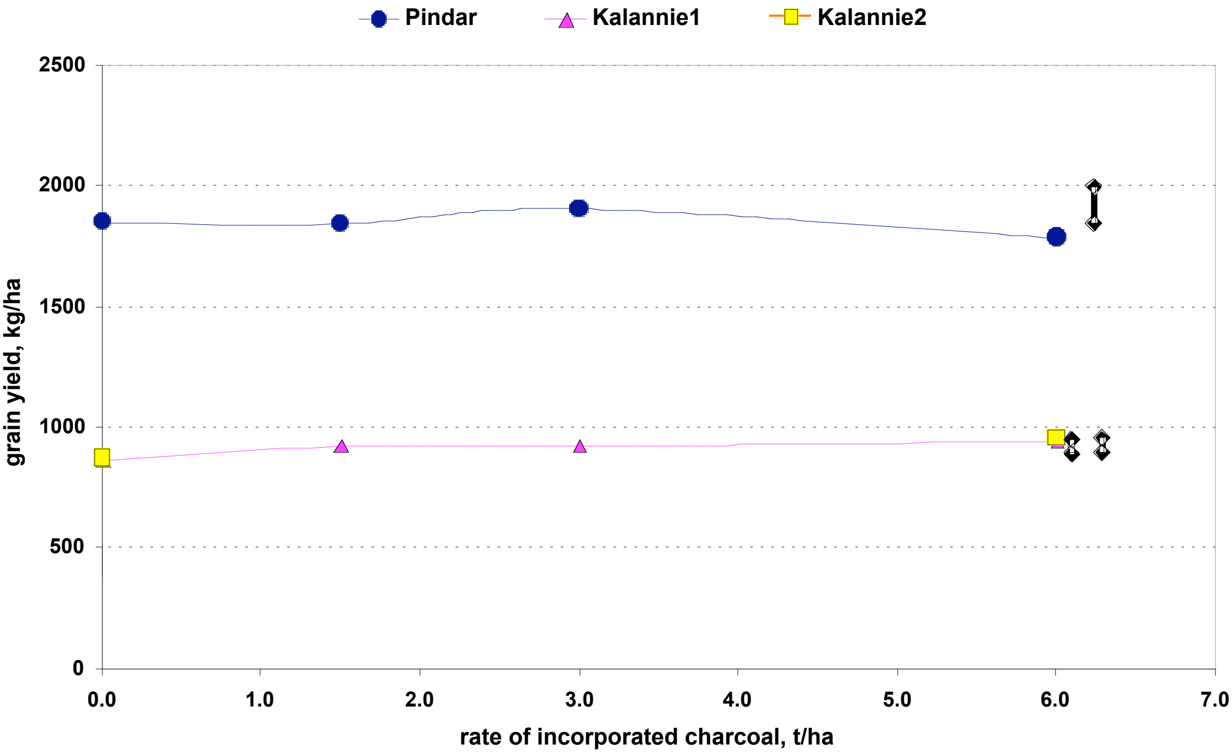

Figure 1. Influence of charcoal addition on grain yield for recommended soluble fertiliser rate at Pindar and Kalannie; the points for experiment 2 at Kalannie have very similar positions on the graph as the points for experiment 1 at Kalannie. Lsd values for $P<0.05$ are shown as vertical bars.

Charcoal addition had little or no effect on grain yield using recommended rates of soluble fertiliser at Pindar or Kalannie, figure 1; see tables 7, 14 and 15. The statistically significant yield increases, at Kalannie, are small; 57kg/ha (6%) @ 1.5 t/ha of charcoal and 76 kg/ha (9%) @ 6 t/ha of charcoal; $P<0.1$. The crop fertilised with recommended rates of soluble fertiliser had an adequate supply of phosphorus and other nutrients, thus perhaps the symbiotic biological supply, which requires more energy per unit P supply, would not be encouraged; however the research literature is not conclusive about this hypothesis (Gazey et al. 2004).

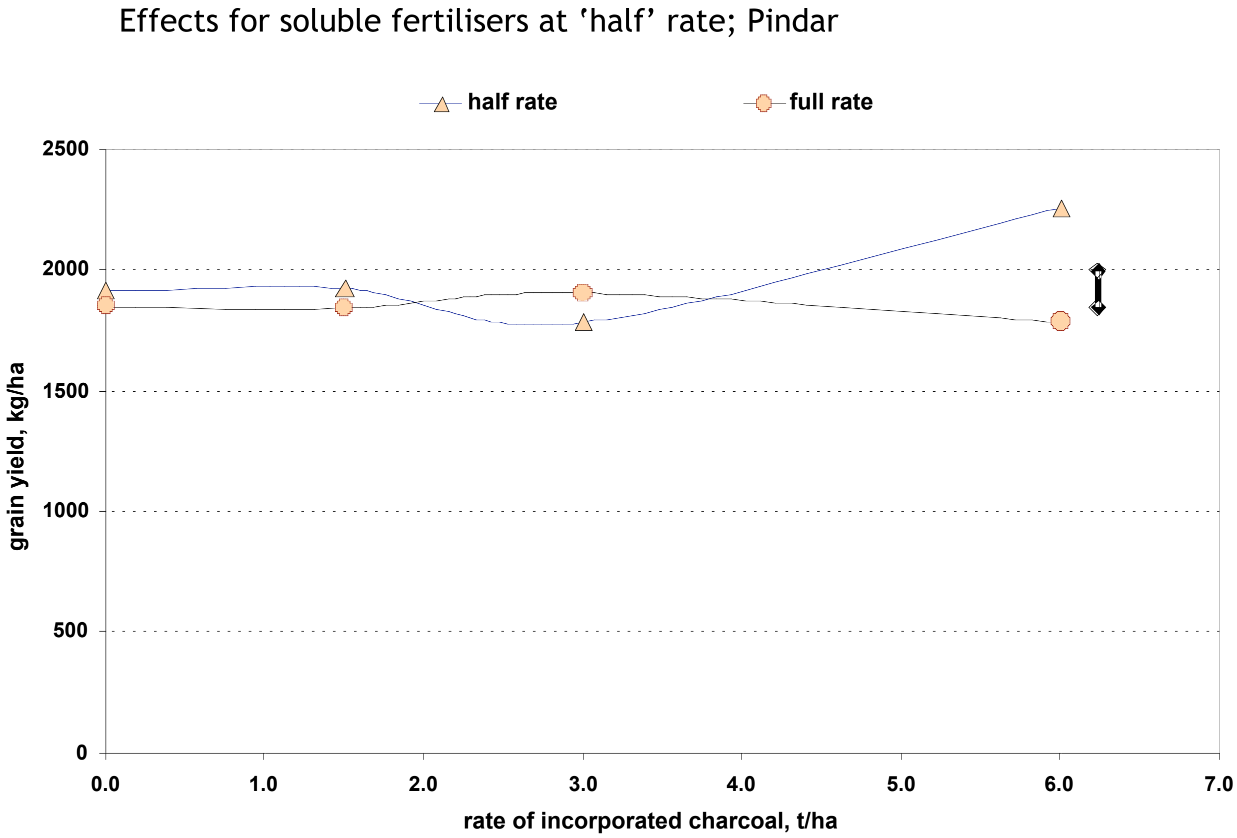

Figure 2. Influence of charcoal addition on grain yield for low rates of soluble fertiliser use at Pindar, compared to recommended rates. Lsd values for P<0.05 are shown as vertical bars.

At approximately half the recommended rate of soluble fertiliser and the highest rate of charcoal addition (6 t/ha) there was a yield benefit of about 344 kg/ha (18% more than without charcoal); figure 2 and table 7. This could not be associated with any component of yield. This treatment is also associated with increased early uptake of nutrients, partly due to more biomass and a trend to higher tissue concentrations; table 5a and 5b. Some of this extra nutrition may come from within the charcoal at the higher rate of charcoal addition and explain the improved yield of the 6t/ha charcoal rate treatment.

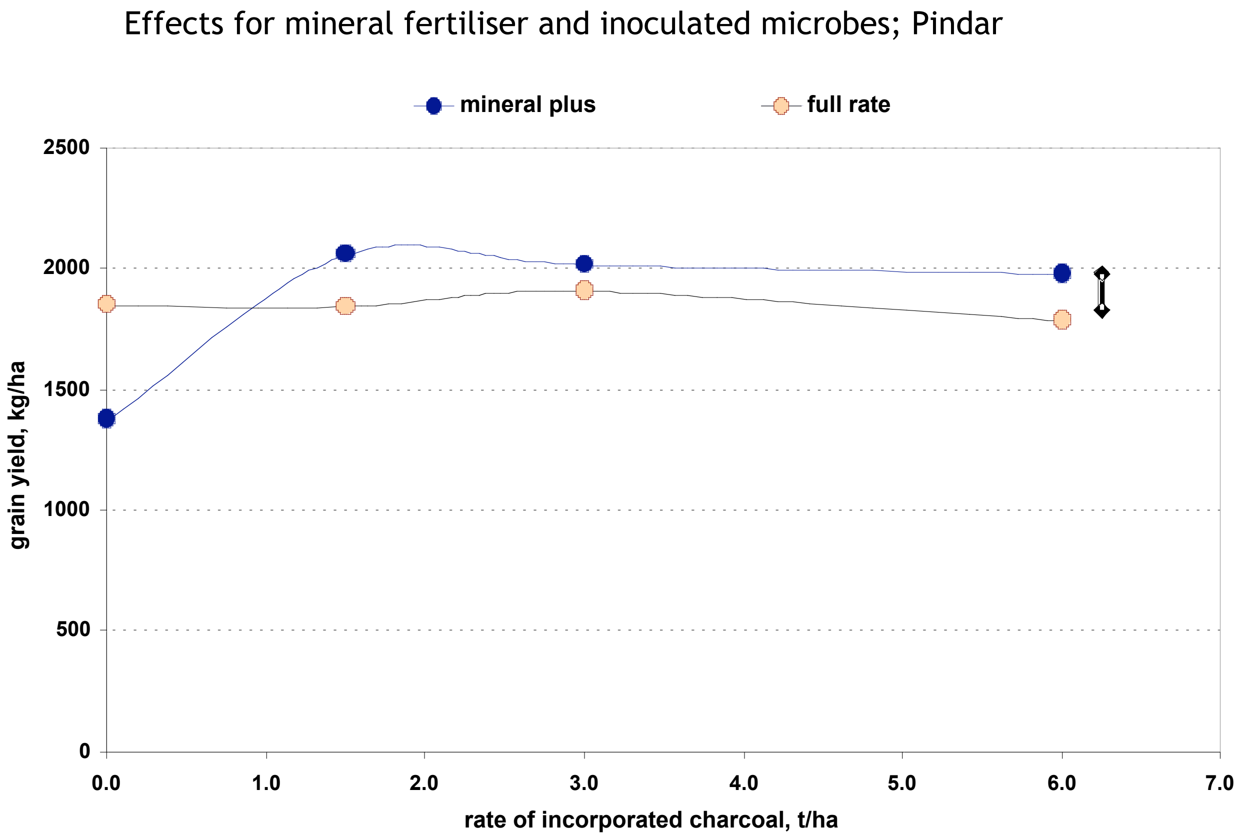

Figure 3. . Influence of charcoal addition on grain yield for mineral fertiliser and inoculated microbes at Pindar, compared to recommended rates of soluble fertiliser. Lsd values for P<0.05 are shown as vertical bars.

Addition of only 1.5 t/ha of banded charcoal to wheat growing with mineral fertiliser and inoculated microbes resulted in about 640 kg/ha grain yield increase (46% of the untreated yield); figure 3 and table 7. This improvement was most clearly associated with an increase of number of grains set per wheat head (figure 4) and also associated with improved AM fungal colonisation of wheat roots (figure 5). The early N and P supply was sufficient for all treatments at Pindar and the improvement of yield by charcoal is not associated with improvements in tiller establishment. Thus it is unlikely that initiation of grains at a very early growth stage (the earliest few leaves) would be influenced by N or P supply. Loss of grains per head is then likely to have occurred in later growth stages when the plants experienced drought stress. Perhaps the extra AM colonisation by September, induced by the presence of charcoal and shown in table 6, assisted water uptake to the crop; see figure 5.

Figure 3 shows grain yield by the mineral fertiliser treatment and charcoal is close to significantly greater (at $P < 0.05$) than the soluble fertiliser at any level of charcoal. However, this comparison is compromised, because the plant establishment by the two fertiliser regimes was different (table 3). The plant population with the mineral fertiliser was about 80 plants/m^2, while the population with the normal rate of soluble fertiliser was about 140 plants/m^2. Lower plant density at the same site was found to provide yield advantage in the same season, due to reductions of early biomass, conservation of soil moisture pre-anthesis, reduced drought stress, less tiller loss and better grain survival (Blackwell et al. 2006).

Plant and soil properties associated with yield differences by charcoal incorporation.

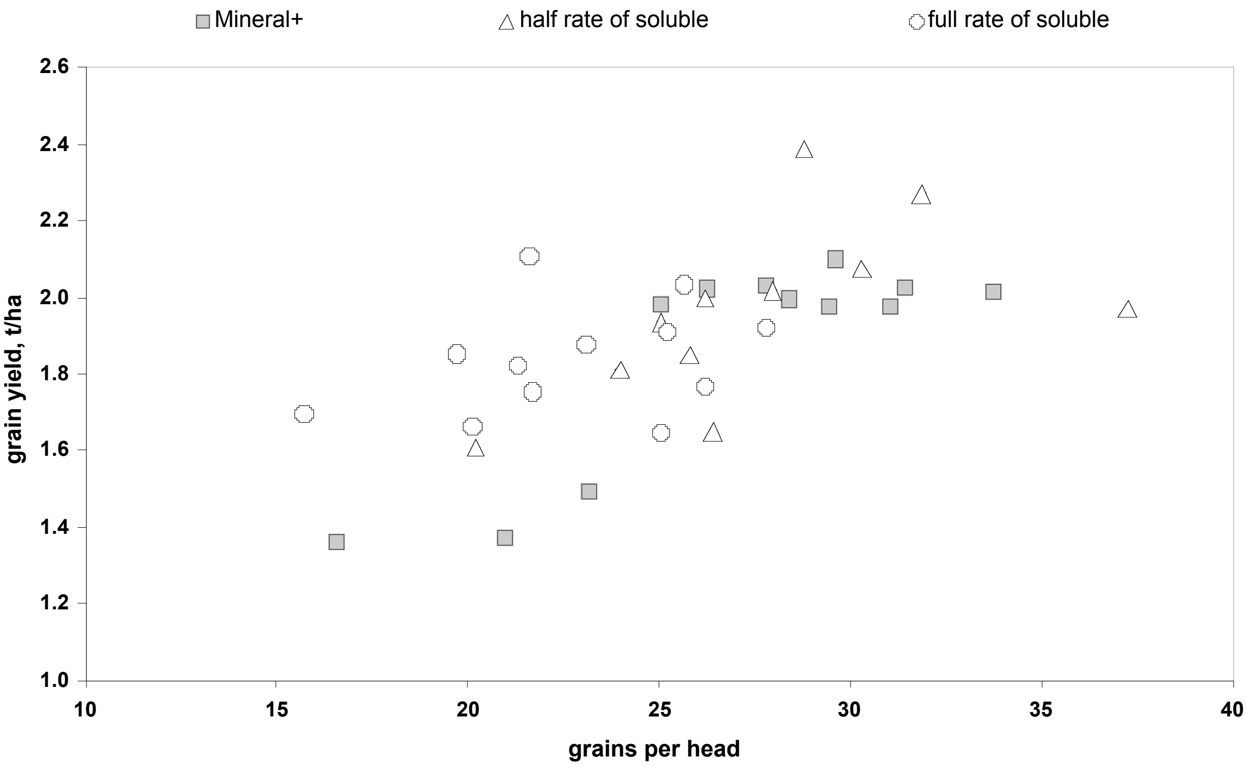

Figure 4. Association between grain yield and grains per head for plots with the full rate of soluble fertiliser, half the rate of soluble or mineral fertiliser and inoculated microbes. All charcoal incorporation rates are included in each data set; the rate of charcoal tends to increase as the no of grains per head increases.

Grains per head had the strongest correlation with grain yield, compared to heads/m^2 and grain weight. The trends for data from all the plots are shown in figure 4. Linear regression between yield and grains per head explained 42% of variation for all treatments, 10% for the high rate of soluble fertiliser, 32% for half rates of soluble fertiliser and 73% of variation for the mineral fertiliser.

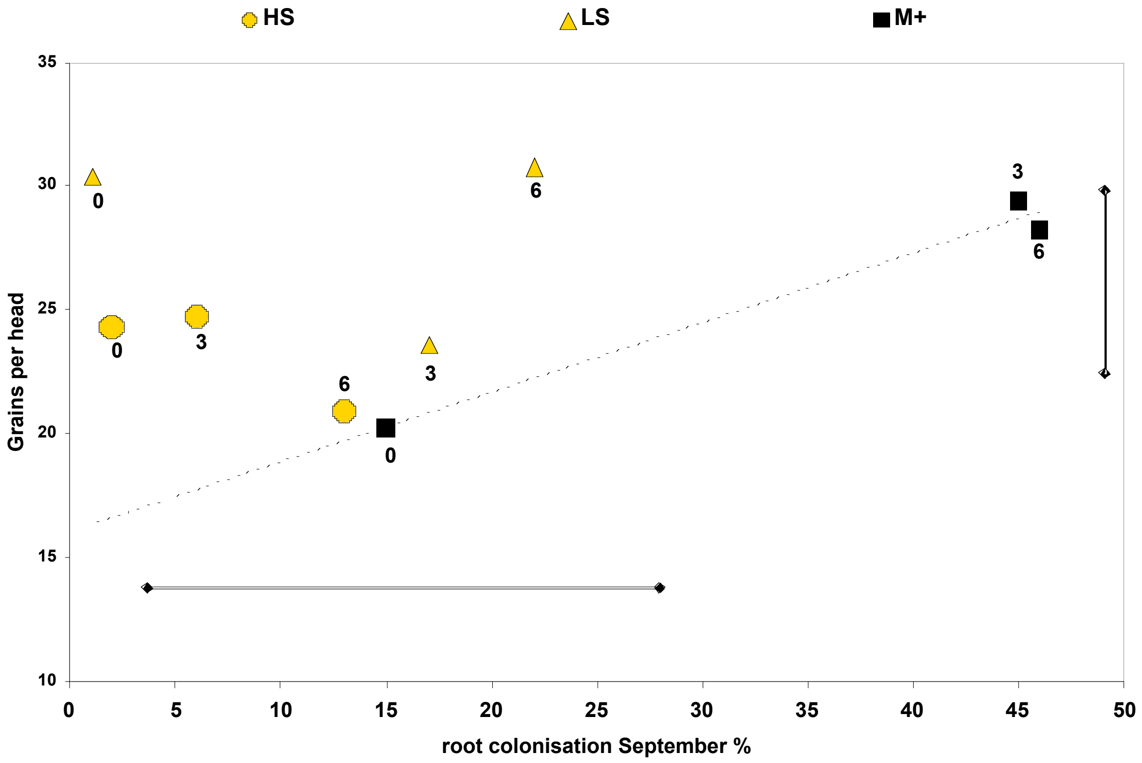

Figure 5. Relationships between root colonisation by AM fungi in September and grains per head at harvest for the three fertiliser regimes and three rates of incorporated charcoal at Pindar. HS = high rate of soluble fertiliser, LS = low rate of soluble fertiliser and M+ = mineral fertiliser with inoculated microbes. The numbers below or above each point are the rates of incorporated charcoal in t/ha in the 100 mm bands. The vertical and horizontal bars indicate the least significant differences between any combination of fertiliser regime and charcoal rate at $P<0.05$.

Charcoal incorporation enabled more root colonisation during the later part of the growing season in the mineral fertiliser treatments and is strongly associated with more grains per head; figure 5. When combined with the visual impression of a larger root system than plants grown with soluble fertiliser, the large root colonisation of the mineral fertiliser treatments with charcoal (about 45%) suggests an even larger amount of AM hyphae exploring the surrounding soil than for root systems grown with soluble fertiliser and without charcoal.

Such an extension of the crop root system by hyphae of AM fungi may have assisted in better access to water during the period of mid-winter drought (July to mid August) at Pindar. It may also have enabled access to the inter-row fertiliser to provide additional nutrition later in the growing season. Neumann and George (2004) found evidence that AM fungi could improve P and water supply to the crop from dry soil. Field evidence of improved tolerance of a drought sensitive wheat variety by AM colonisation was identified by Al-Karaki et al. (2004). Their results also identified associations between grain yield and grains per head, as well as grains per head and root colonisation by AM. Thus there is some support for the hypothesis that the extra volume of fungal hyphae from AM colonisation can assist wheat tolerance of drought stress and protect some yield.

Figure 5 shows a trend of reduced grains per head with AM colonisation of roots when full rates of soluble fertiliser were used. There was also a trend for less early growth as charcoal incorporation rate increased (figure 6) when recommended rates of soluble fertilisers were used, as well as more AM colonisation of roots for the same treatments and fertiliser regime (table 6). AM activity was not measured at Kalannie, but the increased uptake of zinc with incorporated charcoal (table 12) suggests there was AM activity. Al-Karaki et al. (2004) identified AM improves zinc supply to plants in field experiments. These observations support the hypothesis that in conditions rich in soluble phosphorus, AM can behave more parasitically than symbiotically when AM activity is improved by incorporation of charcoal.

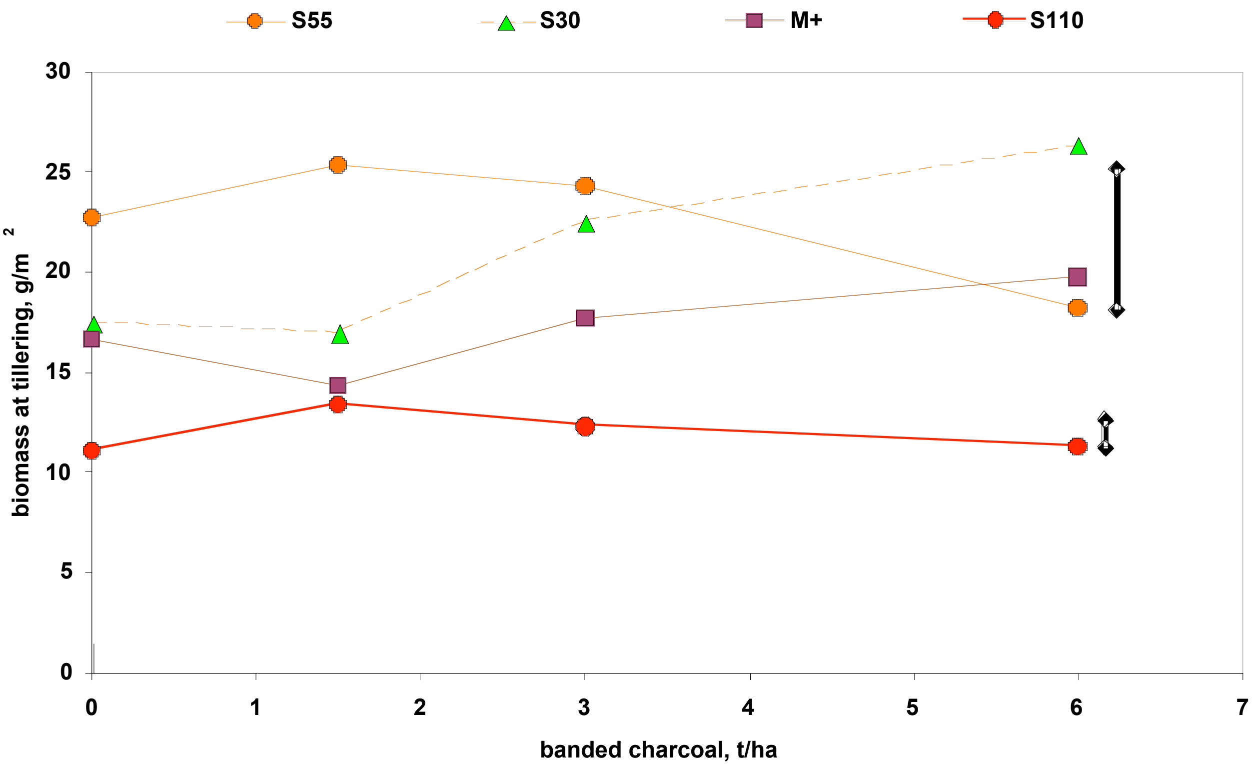

Figure 6. Relationships between banded charcoal rate and crop biomass at tillering for fertiliser treatments of 55 kg/ha of soluble fertliser (S55), 30 kg/ha of soluble fertiliser (S30) and mineral fertiliser with inoculated microbes (M+) at Pindar and 110 kg/ha of soluble fertiliser (S110) at Kalannie. The Lsds for any treatment comparison at Pindar and any treatment comparison at Kalannie are shown as vertical bars.

Economic analysis

If the effects of the treatments at site 1 (Pindar) only persist for one season and the costs of acquiring and incorporating charcoal are more than the financial benefits, the most profitable treatment is the low rate of soluble fertiliser with no charcoal incorporation. Skjemstad et al. (2001) show charcoal can be very resistant to microbial decomposition, so the benefits for soil microbes may persist for more than one year. The value of the charcoal effect on yield increases in the trial is estimated in table 16. The yield improvement for the mineral fertiliser is equivalent to a value of about $100/t of the oil mallee charcoal used in the trial or approximately $2/kg of carbon content. These values, combined with the discounted value of yield benefits in subsequent seasons, would be help estimate the true economic value of adding oil mallee charcoal to these soils and with the fertilisers used. The potential to achieve a commercial return from the sequestration of charcoal as an offset for carbon dioxide emissions in broadscale agriculture will also help calculate true economic value. The potential supply of charcoal from Mallee can be estimated from Bartle et al. (2007). They estimate that in optimistic conditions, Western Australia can produce 9.6 million dry tonnes of mallee biomass per year.

Table 16. Calculations of the financial value of yield improvements by charcoal addition. The broad acre equivalent of the charcoal is the same weight of charcoal in the bands applied to the whole area.

Trial site#	yield benefit	banded charcoal	broad acre equivalent		value ($/ha) for wheat at		carbon value
and fertiliser	kg/ha	t/ha	kg/ha charcoal	kg/ha carbon	$150/t	$250/t	$/kg C#
1. 100 kg/ha **mineral+**[1]	640	1.5	250	**56**	96	160	**2.84**
1. 30 kg/ha **soluble**[2]	344	6.0	1000	**225**	52	86	**0.38**
2. 110 kg/ha **soluble**[3]	76	6.0	1000	**225**	11	19	**0.08**
3. 110 kg/ha **soluble***	83	3.0	620*	**140**	12	21	**0.15**

wheat at $250/t

[1]cost $46.5/ha [2] $15.3/ha [3]$50/ha *300 mm row spacing and adjusted to 6% moisture

Conclusions

There were encouraging effects of charcoal on Arbuscular Mycorrhiza (AM) colonisation. Banded oil mallee charcoal improved AM colonisation of wheat roots by 3 fold, when used with mineral fertilisers and AM is inoculated with the seed in the acid sandy clay loam with a low population of indigenous AM. Early phosphorus uptake was not improved by AM colonisation; P supply from the soil and applied fertiliser was already adequate.

AM colonisation in spring was related to effects of charcoal application on grain survival in inoculated mineral fertiliser treatments. This infers AM hyphae may have improved water supply to reduce drought stress and loss of grains in these treatments.

Potential benefits

1. There were small profits, in terms of wheat production, for incorporation of oil mallee charcoal up to 225 kg/ha of carbon in sandy soils with adequate P supply, when using recommended rates of soluble fertiliser (55-110 kg/ha).
2. There may be some net financial benefit from addition of deep banded charcoal at 225 kg/ha or more of carbon in sandy soils with adequate P supply when using half rates of recommended soluble fertiliser (30 kg/ha). However the costs of charcoal manufacture and incorporation are poorly known.
3. There is more opportunity for net financial benefit from use of oil mallee charcoal with of mineral fertilisers and inoculated soil microbes, on shallow sandy soils which experience drought. However the long term effect of established colonies of soil microbes, enabled by a charcoal habitat, and the need to replenish reserves of soil nutrients other than nitrogen is unknown.
4. The financial benefit of incorporating charcoal into wheatbelt farming systems could be substantially increased if payments were made for the carbon dioxide sequestered by incorporating charcoal. Preliminary modelling using conservative costs and returns for increased wheat yields and the production of eucalyptus oil indicate the cost per carbon dioxide tonne sequestered in an integrated short rotation mallee coppice system ranged from $6 to $15 Shea (2005 unpublished)

R and D needs

- There is a need for longer term information on the efficacy of charcoal induced crop nutrition benefits.
- There is also a need for clearer estimation of the costs of manufacture and incorporation of oil mallee charcoal and the potential returns from carbon sequestration.
- A clearer understanding of the potential benefits of charcoal to agriculture would need some comparative evaluation of the effects of charcoal from all possible agricultural sources; including oil mallee. Cereal chaff may have extensive potential because it is often currently disposed of to help control weeds.

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