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Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia

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ABSTRACT

Subsoil constraints are major limiting factors in crop production in many soils of southern Australia. A field study examined effects of deep incorporation of organic and inorganic amendments in 30–40 cm on soil properties, plant growth and grain yield of wheat (*Triticum aestivum* var. Ambrook) on a Sodosol with dense sodic subsoil with or without lucerne history in a high rainfall region (long-term average annual rainfall 576 mm) of Victoria. Amendments were applied at a rate of 10–20 t ha^{-1}. Deep ripping alone and deep ripping with gypsum did not significantly affect grain yields. In comparison, application of organic materials doubled biomass production and increased grain yield by 1.7 times. Organic amendment-treated plots produced 60% more grains per area than the untreated control. The crop extracted over 50 mm extra water from below 40 cm soil in organic amendment-treated plots than the untreated control. Nitrogen uptake was almost doubled (403 kg ha^{-1}) in the organic amendment-treated plots than the untreated control (165 kg ha^{-1}). The improved yield with amendments was related to an increase in plant available water in the hostile subsoil, and prolonged greenness of leaves and supply of nitrogen and other nutrients.

1. Introduction

A feature of the Australian land surface is the widespread occurrence of duplex, texture-contrast soils (Tennant et al., 1992). These soils, in which clay subsoil lies beneath a coarser-textured surface soil (Northcote, 1979), occur on much of the arable land in the south-west and south-east of the Australian continent. There is now a widespread awareness that the clay subsoil limits the performance of crops that grow on these soils (Gardner et al., 1992; Rengasamy, 2002; Wong and Asseng, 2007). In the high rainfall zone of south-west of Victoria, a survey of subsoil properties in duplex soils found that the clay subsoils were very sodic with exchangeable sodium percentages ranging from 14% to 22% and that bulk densities were high, ranging from 1.5 to 1.7 g cm^{-3} (Newton et al., 2006). Root growth in soil layers is severely restricted and so the clay subsoil below 50–60 cm tend to remain continuously moist, as crops are unable to extract the deep subsoil water.

Such soils present problems for crops in the high rainfall zone. The soils tend to become waterlogged on top of the relatively impermeable clay layer early in the growing season when winter rainfall exceeds evaporation (Gardner et al., 1992), while there may not be sufficient plant available water above the clay for the crops to reach their potential yield at the end of the growing season, particularly if there is a dry finish to the season (Wong and Asseng, 2007). It is not surprising therefore that many crops in the region yielding no more than one third of their potential (Riffkin and McNeil, 2006).

Numerous attempts have been made to ameliorate these subsoil constraints in duplex soils. These have invariably involved deep ripping and the incorporation of high rates of gypsum in the subsoil (Jayawardane and Chan, 1994). Additional treatments have involved subsoil fertilizer applications, underground drainage and supplemental spray irrigation. Despite some 20 years of investigation into subsoil modification to improve the growth of irrigated forage and crop production on duplex soils (Mason et al., 1984; Pritchard et al., 1988; Olsson et al., 2002; Greenwood et al., 2006a,b), there have been no farming technologies developed to improve the subsoils. In a recent publication, Greenwood et al. (2006a) concluded that subsoil modification to improve irrigated forage production on a commercial scale was not feasible at the present time. Similarly, attempts to improve subsoil properties in duplex cropping soils in the high rainfall zone, involving the use of gypsum and deep ripping, did not meet with success (Ellington, 1986; Gardner and McDonald, 1988; Clark, 2004).

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One management strategy that might improve the root growth of crops in dense clay subsoils is the prior use of ‘primer crops’. These plants have roots that can grow down into dense subsoils and in doing so create root channels or biopores (>2 mm) that will increase rainfall infiltration into the subsoil (Yunusa and Philip, 2003). A candidate plant is lucerene (*Medicago sativa*), which has previously been recommended for use in the high rainfall zone due to perceived agronomic benefits for the crop rotation (Gardner et al., 1992). It is possible that the increased development of root channels into the clay subsoil, following a lucerne phase, may assist the growth of crop roots into the subsoil during the subsequent cropping phase. This possibility needs to be tested in the field.

A further management option for ameliorating dense clay subsoil is the deep incorporation of organic material into the subsoil layers. This was proposed by Ellington (1986) as a means of improving subsoil aggregation, porosity and biological activity in the deeper soil layers. This was trialed in the South Australian Mallee, and a 3-fold increase in plant growth was obtained by removing topsoil layers in a farmer’s paddock and placing lawn clippings and fertilizer in the trench, before returning the topsoil (Graham et al., 1992). Such interventions would be expensive, as they would require significant mechanical intervention. However, crops in the high rainfall zone, with higher rainfall and a longer growing season, have higher yield potentials than crops from the drier cropping zones. Such crops may provide cost-effective yield responses to these types of interventions.

This paper reports on the performance of winter wheat crop at two adjacent sites on duplex soil in south-west Victoria, following different subsoil amelioration treatments. The treatments included deep ripping and the incorporation of different inorganic and organic amendments at a depth of 30–40 cm beneath raised beds in the early autumn of 2005. The experiment was carried out in a continually cropped, and in an adjacent paddock that had a 4-year history of grazing lucerne from 1999 to 2003. This will also indicate whether lucerne has a role to play in improving crop production on duplex soils in the high rainfall zone.

2. Materials and methods

2.1. Site

The trial site was located at Yaloak estate near Ballan, Victoria (longitude 144.23, latitude −37.86, 508.7 m height). Two paddocks were selected to apply the treatments. One paddock had 4 years of lucerne history (*M. sativa* cv. Cimaron.) during 1999–2003, followed by a canola crop in 2004. Lucerne was sprayed with roundup (glyphosate) in August 2003. The other paddock adjacent to the lucerne paddock was under continuous cropping (canola–wheat–barley–wheat–canola). Both paddocks are under permanent raised beds (1.7 m wide centre to centre) for last 8 years.

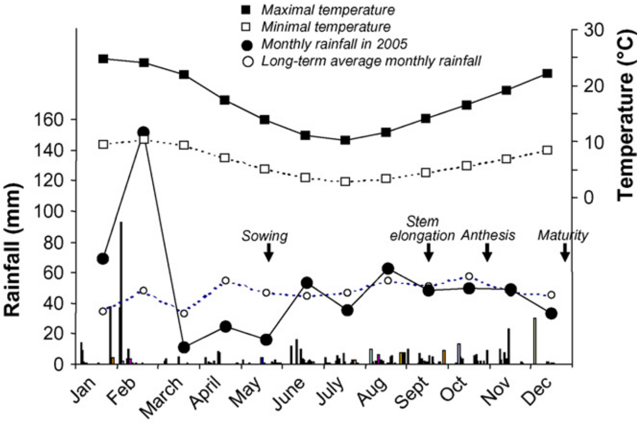

Fig. 1. Monthly average maximal and minimal temperatures and long-term average monthly rainfall and monthly and daily (bars) rainfall at the experimental site in 2005. Long-term average monthly data were obtained from the weather station at Ballan, Victoria, Australia.

Long-term average rainfall at the site is 576 mm dominating in winter and spring (from April to October). Average mean maximum and minimum temperatures and rainfall and growing season rainfall during 2005 are given in Fig. 1. The soil of both paddocks was a Sodosol (Isbell, 2002) with dense sodic subsoil. Basic soil properties are listed in Table 1.

2.2. Experiment design and treatments

The field trials were established in 2005. The trial on each paddock was a randomized block design with nine treatments (Table 2) in four blocked replicates. The size of each plot was 5 m long raised bed (1.7 m wide). With a buffer bed in between two treated side-by-side beds and 2 m buffer was between length sides of each treated bed. Two beds were left as buffer between blocks with 3 m buffer along beds in each block.

The amendments were applied manually at 30–40 cm deep with the help of a pipe (15 cm diameter) attached to a deep ripper. Organic amendments were in pellet form as they were easy to apply manually. Dynamic lifter® had 4% N, 2.2% P and 1.9% K, and lucerne pellet had 2.8% N, 0.9% P and 1.4% K. There were two strip lines on each 1.7 m bed (centre to centre) (Fig. 2). Treatments were applied 1 week before sowing of the crop.

Table 1
Chemical and physical properties of the soils at different depths of the lucerne and non-lucerne sites

Experimental site	Depth (cm)	pH[a] ($CaCl_2$)	EC (1:5)[a] (dS m^{-1})	Organic C[a] (%)	Nitrate N[a] (mg kg^{-1})	Clay[b] (%)	Exchangeable cations[a] (cmol kg^{-1})	Exchangeable sodium percentage[a] (%)	Bulk density[c] (g cm^{-3})	Volumetric water content θv	
										30 kPa (%)	1500 kPa (%)
Lucerne site	0–10	5.8	0.11	4.15	18	51	19.2	11.4	1.03	38	18
	10–20	6.0	0.08	2.85	8	55	21.3	13.6	1.32	39	20
	20–40	6.2	0.07	2.02	8	59	23.4	17.5	1.52	46	27
	40–60	4.6	0.09	2.63	15	62	26.8	20.9	1.62	48	30
Non-lucerne site	0–10	5.2	0.10	3.29	7	55	18.6	12.9	1.07	40	19
	10–20	7.2	0.24	3.81	17	58	23.8	14.7	1.38	42	21
	20–40	5.7	0.08	2.54	7	61	24.6	17.1	1.46	48	29
	40–60	5.7	0.07	2.08	3	64	25.7	20.3	1.7	52	34

[a] Rayment and Higginson (1992).

[b] Hydrometer method.

[c] From intact cores.

Table 2
Description of the treatments used in the field trials

Treatment	Description	Amount of amendment added and tillage
1	Control	Direct sowing
2	Deep ripping only	To 40 cm depth
3	Gypsum	10 t ha^{-1} incorporated in 30–40 cm depth
4	MAP	100 kg ha^{-1} of mono-ammonium phosphate (MAP) incorporated in 30–40 cm depth
5	Lucerne pellets	20 t ha^{-1} incorporated in 30–40 cm depth
6	Dynamic lifter	20 t ha^{-1} incorporated in 30–40 cm depth
7	Sand	20 t ha^{-1} incorporated in 30–40 cm depth
8	Gypsum + MAP	10 t ha^{-1} gypsum and 100 kg ha^{-1} MAP incorporated in 30–40 cm depth
9	Lucerne pellets + gypsum + MAP	20 t ha^{-1} lucerne pellets + 10 t ha^{-1} gypsum + 100 kg t ha^{-1} MAP incorporated in 30–40 cm depth

2.3. *Crop growing conditions*

Wheat (*Triticum aestivum* var. Amarok) was sown on the first week of May 2005 at a seeding rate of 70 kg ha^{-1}. Amarok is a long-season winter variety with yield potential ranging from 7.8 t ha^{-1} in Victoria, Australia and 12 t ha^{-1} with supplementary irrigation in New Zealand. Mono-ammonium phosphate (MAP) was applied at 70 kg ha^{-1} as a basal at the time of sowing. Crop was sown at a row spacing of 20 cm and 7 rows across the raised bed (Fig. 2) after spraying roundup (glyphosate) at 1.2 l ha^{-1}. Post-sowing herbicides MCPA500 [(4-chloro-2-methylphenoxy) acetic acid] at 0.3 l ha^{-1} and Diurex (Diuron WG) at 100 g ha^{-1} were used to control weeds 40 days after sowing. As winter rainfall in 2005 was low, the farmer decided not to apply N fertilizers. Crop was harvested in the second week of January 2006.

2.4. *Crop and soil measurements*

Number of plants and number of tillers per square meter were measured 20 days after emergence and at tillering. Reading was taken from two random quadrants (0.5 m^2) from each replication. Plant height was monitored during the crop growth. Six random plants were harvested at each growth stages for biomass monitoring and nutrient analysis as the small plot size restricted us taking quadrant samples for biomass measurement. As observed near maturity plants with organic amendments remained greener than control untreated plants. We measured this greenness by giving a score in 1–7 scale where 1 was for uniform yellow and 7 was for uniform green.

Plant materials were dried in well-ventilated oven at 70 °C. Dried plant samples were then grinded in a willey mill. Plants were analysed for N and S using Elementar Vario EL analyser (Elementar Analysensysteme GmbH, Hanau, Germany). The concentrations of Ca, Na, Mg and K in shoots were measured by atomic absorption spectrometer following nitric acid digestion. Nitrogen uptake was calculated from total N concentration in shoots and shoot biomass. Nitrogen harvest index (NHI) was calculated as ratio of N in grain to total plant N uptake.

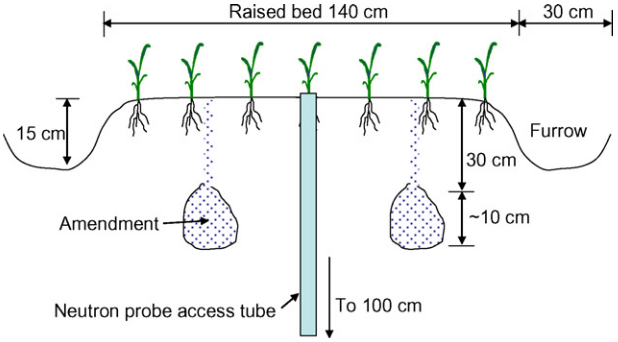

Fig. 2. A cross-section diagram of the raised bed showing crops rows, neutron probe access tube and amendment placement in the subsoil.

For grain yield and yield parameters at maturity, plants were harvested in a quadrant (0.5 m^2) on top of bed (1.7 m wide centre to centre, 1.4 m top of bed) from each replication. Biomass was taken and then sub-samples (10 ears) were taken to measure yield parameters, including ear length, spikelets per ear, kernel weight, kernel number of per ear, ear number per m^2 and kernels per m^2. Grains were harvested by hand and grain yield was calculated. Results on a hectare basis were corrected for 20% land lost in furrows.

Water content (θv) in soil profiles was monitored during the crop growth with the help of a Neutron Probe (Tang et al., 2002). Access tubes were installed at the middle of the raised bed (Fig. 2) in each replication of six selected treatments (treatments 1, 2, 3, 7, 8 and 9). Calibration of the Neutron Probe was done by measuring the gravitational soil water and bulk density at different depths from the soil column removed for the installation of access tubes. Neutron count reading was taken at each 20-cm depth immediately after installing the access tubes. The amount of water used by the crop, from soil profile, was calculated from the difference in soil water content at the time of sowing and at maturity and was expressed in mm. The soil water content in mm was calculated by multiplying the volumetric water contents with soil depth in mm.

2.5. *Statistical analysis*

Analysis of variance was computed using Genstat 5 (Lawes Agricultural Trust, Rothamasted, UK). The LSD at $p = 0.05$ was computed and used for comparing the effects of treatments. Analyses for the lucerne and non-lucerne sites were performed independently.

3. Results

3.1. *Crop growth*

Consistent treatment differences in crop growth occurred at the stem elongation and booting stages of growth, at the two experimental sites. The crops with the shortest stems generally grew on the control, deep-ripped, and the deep-ripped plus gypsum or MAP plots, at both sites (Table 3). In contrast, the tallest wheat plants at these growth stages grew on the plots amended with dynamic lifter® pellets or on the gypsum plus MAP plots; their stem heights were around 5–8 cm taller than those on the control plots at the lucerne and non-lucerne sites, respectively at stem elongation, but the differences increased to 13–15 cm at the booting stage of growth. The other organic amendment treatments involving lucerne pellets, both with and without MAP and gypsum additions, together with gypsum plus MAP and the coarse sand treatments consistently resulted in significant increases

Table 3
Pre-anthesis stem heights, and shoot biomass yields at anthesis of wheat cultivar (var. Amarok) grown in various treatments, at the two experimental sites under different treatments

Treatment	Non-lucerne site			Lucerne site		
	Stem height (cm)		Biomass at anthesis (t ha^{-1})	Stem height (cm)		Biomass at anthesis (t ha^{-1})
	Stem elongation	Booting stage		Stem elongation	Booting stage	
Control	23.2	44.3	8.2	25.0	50.8	10.3
Deep ripping	24.3	47.5	7.0	25.8	50.8	9.9
Inorganic amendment						
Gypsum	24.6	47.8	12.1	27.0	54.3	12.2
MAP	26.2	51.5	11.4	28.0	52.0	13.8
Gypsum + MAP	27.2	51.5	14.9	30.0	62.0	14.4
Coarse sand	28.2	57.3	14.8	29.0	57.5	13.8
Organic amendment						
Dynamic lifter®	31.2	59.8	15.4	30.8	59.5	17.4
Lucerne	28.2	54.5	16.4	30.0	57.0	17.2
Lucerne + MAP + gypsum	30.6	58.5	13.5	28.8	61.3	15.2
LSD ($p = 0.05$)	2.9	3.5	3.0	2.3	2.9	4.0

($p < 0.05$) in stem height, compared to the control and deep-ripped treatments.

Organic amendments also produced the largest responses in shoot biomass at flag leaf emergence at both experiments. The dynamic lifter® pellets, or the straight lucerne pellets produced the largest responses, almost doubling biomass yields compared to the control plots at the non-lucerne site, with smaller biomass increases of around 70% occurring at the lucerne site (Table 3). Lucerne pellets plus gypsum and MAP produced somewhat smaller biomass yields at anthesis, but these were still significantly ($p < 0.05$) greater than those of the control and deep-ripped treatments.

Smaller biomass responses occurred with the inorganic amendments compared to the organic amendments, and responses were smaller at the lucerne site compared with the non-lucerne site. For example, the addition of gypsum, or MAP, in the ripped trenches increased biomass yields above the controls by around 20–30% at the lucerne site and around 40–50% at the non-lucerne site (Table 3). Surprisingly, the coarse sand amendment resulted in biomass yields of 34% and 80% above the biomass grown on the control plots at the lucerne and non-lucerne sites, respectively. The largest biomass responses to inorganic amendments, of between 39% and 82% at the lucerne and non-lucerne sites, respectively, occurred when gypsum and MAP were added together.

3.2. Grain yield and components

High grain yields of 11 t ha^{-1} and above occurred at both sites in 2005 where straight organic amendments were added to the subsoil prior to the start of the growing season. The highest yields consistently occurred with the dynamic lifter® amendment, followed by the use of straight lucerne pellets (Tables 4 and 5), with yields at the non-lucerne site being generally 1.5–2 t ha^{-1} heavier for these highest yielding treatments, compared to the site with the lucerne history. These highest yielding treatments resulted in yield increases of 70% and 60% above the control at the non-lucerne and lucerne sites, respectively (Tables 4 and 5). The lowest yields at both sites occurred on the control and deep-ripped plots, while intermediate grain yields were produced with the inorganic amendments, including gypsum, MAP, gypsum plus MAP and coarse sand.

The harvest indices for this long-season, winter wheat cultivar Amarok, grown at both the lucerne and non-lucerne sites at Ballan in 2005, were very high. The index, for 6 of the 9 treatments at both sites, exceeded 6.0 (Tables 4 and 5). However, there was no consistent treatment effect on the harvest index (HI) at the 2 sites, apart from the dynamic lifter® and the lucerne pellet amendments having the higher indices above 0.63, and the control having among the lowest index less than 0.55.

Table 4
Grain yield, harvest index and components of grain yield of wheat cultivar (var. Amarok) grown in various treatments, at the non-lucerne site

Treatment	Grain yield (t ha^{-1})	Harvest index	Components of yield					
			Ear number (m^{-2})	Ear length (cm)	Spikelet number (ear^{-1})	Kernal number (ear^{-1})	Kernal Number (m^{-2}) × 1000	Kernal weight (mg grain^{-1})
Control	7.6	0.54	330	7.5	19.0	54	17.8	42.7
Deep ripping	8.0	0.63	305	8.1	19.0	60	18.3	43.3
Inorganic amendment								
Gypsum	8.5	0.53	381	7.7	19.0	52	19.8	43.3
MAP	8.5	0.62	341	8.2	20.0	57	19.4	43.7
Gypsum + MAP	10.6	0.66	397	8.3	20.0	60	23.8	45.4
Coarse sand	9.1	0.55	387	7.5	18.0	54	20.9	43.9
Organic amendment								
Dynamic lifter®	13.2	0.65	464	9.1	21.0	63	29.2	45.5
Lucerne	12.9	0.64	476	9.5	21.0	63	30.0	43.3
Lucerne + MAP + gypsum	11.6	0.61	441	8.8	20.0	59	26.0	44.3
LSD ($p = 0.05$)	1.8	0.09	60	0.6	1.3	7	6.4	n.s.

n.s.: not significant at $p = 0.05$.

Table 5
Grain yield, harvest index and components of grain yield of wheat (var. Amarok) grown in various treatments, at the lucerne site

Treatment	Grain yield (t ha^{-1})	Harvest index	Components of yield					
			Ear number (per m^2)	Ear length (cm)	Spikelet number (ear^{-1})	Kernal number (ear^{-1})	Kernal number (m^{-2}) × 1000	Kernal weight (mg grain^{-1})
Control	7.0	0.48	339	7.5	19.5	49	16.6	46.6
Deep ripping	7.0	0.55	293	7.9	19.3	54	15.8	44.8
Inorganic amendment								
Gypsum	9.1	0.62	360	8.2	20.3	58	20.9	43.7
MAP	7.6	0.47	390	7.9	19.3	49	19.1	39.3
Gypsum + MAP	10.2	0.61	397	8.3	20.2	56	22.2	46.4
Coarse sand	9.9	0.60	381	8.6	20.9	57	21.7	45.6
Organic amendment								
Dynamic lifter®	11.6	0.69	402	9.2	21.1	62	24.9	46.8
Lucerne	11.0	0.63	430	9.0	21.4	59	25.4	43.7
Lucerne + MAP + gypsum	9.6	0.60	379	8.7	20.0	58	22.0	43.3
LSD ($p = 0.05$)	2.1	0.08	74	0.4	0.7	5	4.4	2.5

The high grain yields of around 13 t ha^{-1} with the dynamic lifter and lucerne amendments, at the non-lucerne site can be attributed to the high numbers of wheat grains being produced per unit area. There were 40–55% more ears produced per m^2, and up to 15% more grains per ear (Table 4) on plots amended with these organic materials, compared with the control or deep-ripped plots. Importantly, the ears on these high yielding plots were up to 26% longer which enabled up to 10% more spikelets to be produced per ear, than the control and deep-ripped plots. There were no differences in individual grain weights between treatments at this non-lucerne site.

A similar explanation can be given for the high wheat yields with organic amendments at the lucerne site, compared to the control treatment. Again there were 20–27% more ears produced per unit area with the dynamic lifter® and lucerne amendments, and these ears contained 20–26% more grains, compared with the control treatments (Table 5). Longer ears enabled more spikelets to develop in each ear with these organic amendment treatments. Again there were no consistent differences in the grain weights between treatments.

3.3. *N dynamics*

Subsoil amelioration treatments had a major impact on the nitrogen (N) content of the shoots of wheat plants in this study. The most striking effect was the significantly higher ($p < 0.05$) N uptake by shoots from the dynamic lifter® and lucerne amendment treatments, compared with the control or the inorganic amendment treatments (Table 6). These organic amendment treatments generally had more than 2 times the N content in kg N ha^{-1} in their shoots, compared to the control or deep-ripped treatments, at stem elongation, anthesis or at crop maturity, with the differences occurring at both sites. Most striking were the large amounts of N taken up at crop maturity by shoots on the dynamic lifter® and lucerne pellet plots, at the non-lucerne site, with uptake amounts between 370 and 400 kg N ha^{-1}. These amounts contrast with the 170 kg N ha^{-1} which was the average amount in shoots at crop maturity on the control and deep-ripped plots at the non-lucerne site (Table 6). Nitrogen uptake by wheat shoots for the inorganic amendment treatments were generally intermediate between the organic amendment and the control and deep-ripped treatments, both over time and between sites.

The concentration of protein in grains at harvest reflected the N content in the wheat shoots during crop development (Fig. 3). Here the treatments could again be generally divided into 3 groups; the organic amendment treatments resulted in the highest grain protein concentrations of 11–13%, the control, the deep-ripped, and the gypsum treatment had the lowest concentrations between 9% and 10%, while the other inorganic amendment treatments had grain protein concentrations between 9.6% and 11% (Table 6). There was also a trend for higher grain protein concentrations at the lucerne site, particularly for the inorganic amendment treatments, which were around 1% point higher in protein, compared to the non-lucerne site. However, the highest grain

Table 6
Nitrogen uptake by wheat shoots at progressive stages of crop growth, and the nitrogen harvest indices (NHI) and grain protein concentrations at crop maturity of wheat (var. Amarok) grown in various treatments, at the two experimental sites under different treatments

Treatment	Non-lucerne site					Lucerne site				
	N uptake (kg N ha^{-1})			NHI	Grain protein (%)	N uptake (kg N ha^{-1})			NHI	Grain protein (%)
	Stem elongation	Anthesis	Crop maturity			Stem elongation	Anthesis	Crop maturity		
Control	72	91	165	0.92	9.1	69	120	183	0.84	9.9
Deep ripping	70	89	172	0.93	9.2	89	142	164	0.86	9.2
Inorganic amendment										
Gypsum	70	136	172	0.92	8.5	114	180	229	0.90	10.1
MAP	110	120	192	0.94	9.7	125	224	215	0.82	10.7
Gypsum + MAP	101	173	248	0.95	10.1	138	203	269	0.91	11.0
Coarse sand	115	190	208	0.92	9.6	114	192	261	0.88	10.6
Organic amendment										
Dynamic lifter®	170	241	372	0.93	11.9	173	343	332	0.93	12.2
Lucerne	144	271	404	0.94	13.4	154	319	331	0.92	12.5
Lucerne + MAP + gypsum	162	269	326	0.88	11.2	189	293	276	0.92	12.0
LSD ($p = 0.05$)	27	66	46	0.03	0.9	32	56	47	0.04	0.8

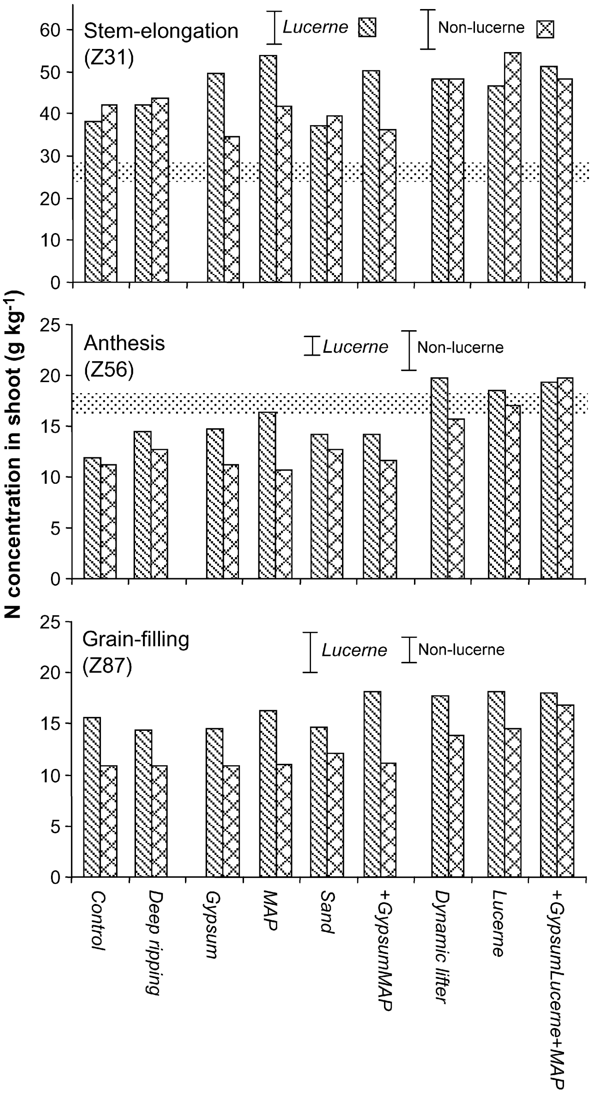

Fig. 3. Shoot nitrogen concentration (g kg^{-1}) at different growth stages under different treatments at two experimental sites. Horizontal shaded bars show the critical nitrogen concentration range below which plants were N deficient (Reuter and Robinson, 1997). Error bars are LSD values at $p = 0.05$ for the lucerne and non-lucerne sites, respectively.

protein concentration of 13.4% occurred with the lucerne amendment treatment at the non-lucerne site.

The major portion of the N in the wheat shoots was translocated to the grain during the grain-filling period in this study. This resulted in very high N harvest indices for all treatments, with the index exceeding 0.9 for most treatments (Table 6). Differences between treatments in the NHI were not apparent at the non-lucerne site; however these indices for the organic amendment treatments were all significantly higher ($p < 0.05$) than those for the control or deep-ripped treatments at the lucerne site. In addition, the N harvest indices were generally higher at the lucerne site, compared to the non-lucerne site, with the differences being most marked for the inorganic amendment treatments (Table 6).

There were also differences between the experimental sites in the pattern of N uptake by wheat shoots during crop development, and these differences depended on the experimental treatments. The differences lay in the amounts of N taken up by shoots between stem elongation and anthesis, compared to the amounts of N taken up between anthesis and crop maturity. The results show that more N was taken up before anthesis at the lucerne site with the organic amendment treatments whereas relatively larger amounts of N were taken up after anthesis with these treatments at the non-lucerne site. For example, an average of 167 kg N ha^{-1} were taken up between stem elongation and anthesis by shoots from the dynamic lifter® and lucerne plots at the lucerne site, but no N was taken up by these shoot post-anthesis during the grain-filling period (Table 6). In contrast, the average N taken up by the shoots from these treatments at the non-lucerne site was 100 kg N ha^{-1} before anthesis and 132 kg ha^{-1} after anthesis. A similar site × treatment interaction occurred with the control and deep-ripped treatments, where relatively more N was taken up before anthesis by shoots from the control and deep-ripped treatments at the lucerne site, compared to the non-lucerne site (Table 6).

3.4. Soil water used

There were significant differences between treatments in the volume of soil water that was extracted from deep soil layers during the cropping period. The effect was particularly marked at the non-lucerne site, where an additional 20 mm of water was lost from the 40 to 60 cm layer with the organic amendment treatment, comprising lucerne plus MAP and gypsum, compared to the control and gypsum treatments (Table 7). Similarly, an extra 32 and 25 mm of soil water was lost from the deepest 60–80 cm soil layer with the organic amendment, compared to the control and gypsum treatments, respectively. However, this effect only occurred from the deep 60–80 cm layer at the lucerne site where extra water loss occurred with the organic amendment, compared to the control and gypsum treatments. Surprisingly, there was practically no water lost from the deep 60–80 cm layer with the gypsum treatment at this lucerne site (Table 7).

The pattern of water loss during the cropping period, from different soil layers within particular soil profiles, also differed between treatments. The notable feature here was the greater loss of soil water from the bottom half of the profile (40–80 cm layer) with the organic amendment treatment of lucerne plus MAP and gypsum, compared to the top 0–40 cm layer of the profile (Table 7). This was more marked at the lucerne site where 112 mm was extracted from the 40–80 cm layer, compared to only 41 mm from the top 40 cm of the profile; similarly 101 mm and 67 mm of soil water were extracted from the bottom and top halves of the soil profile for the organic amendment treatment at the non-lucerne

Table 7
Loss of soil water (mm) from soil profiles between sowing and crop maturity under wheat (var. Amarok) grown in selected treatments at the two experimental sites

Treatment	Non-lucerne site				Lucerne site			
	Depth of soil layer (cm)				Depth of soil layer (cm)			
	0–20	20–40	40–60	60–80	0–20	20–40	40–60	60–80
Control	24.1	33.0	11.8	12.5	16.6	35.6	51.6	34.4
Gypsum	21.3	22.2	14.4	14.8	20.2	12.7	15.4	7.7
Luceren + MAP + gypsum	19.9	32.6	40.0	50.6	18.8	29.2	59.4	61.5
LSD ($p = 0.05$)	n.s.	n.s.	6.2	10.0	n.s.	18.6	16.4	10.8

n.s.: not significant at $p = 0.05$.

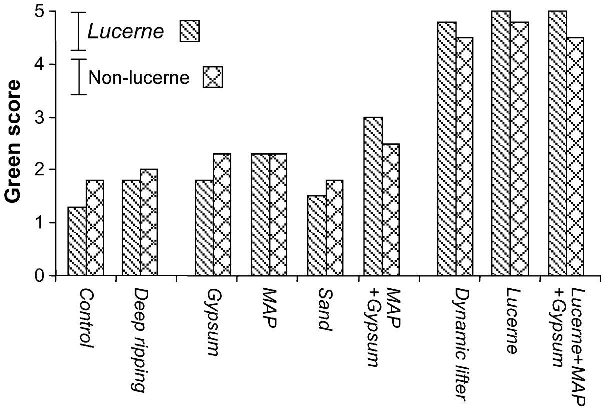

Fig. 4. Greenness score of the flag leaves at the hard-dough stage of grain maturity of wheat grown in various treatments at the two experiment sites. Flag leaf greenness score: 1 = uniform yellow; 7 = uniform green.

site. In contrast, more soil water was extracted from the top half of the profile at the non-lucerne site, with the control and gypsum treatments, compared to the bottom half (Table 7), with a similar effect occurring with the gypsum treatment at the lucerne site.

3.5. Flag leaf greenness

One striking observation made as the wheat plants matured in this study was the flag leaves in some treatments retained their green colour for an extra 1–2 weeks, before finally senescing. The analysis of the flag leaf greenness scores, made at the hard-dough stage of crop maturity, reveals that flag leaves on the organic amendment plots had significantly higher ($p < 0.05$) greenness scores, compared to the control and inorganic amendment plots (Fig. 4). Differences in these scores at both sites were clear cut, with the average scores for the organic amendment treatments being more than 2 times the average score for all other treatments combined. This occurred at both the lucerne and the non-lucerne sites.

4. Discussion

4.1. Grain yield and components of yield

Marked increases in grain yield occurred in both experiments when high rates of organic amendment were incorporated at 30–40 cm depth in the subsoil in the high rainfall zone (HRZ). The high yields of 11–13 t/ha have not previously been reported for wheat crops in Australia. The maximum dryland wheat yields in Western Australia, reported by Zhang et al. (2006), were 5–7 t ha^{-1}, while yields from experiments in the HRZ in southwest Victoria reached 7–8 t ha^{-1} (J. Sheehan, personnel communication). Furthermore, Stapper (2007) reported maximum wheat yields of around 8–10 t ha^{-1} in irrigated wheat experiments in the Lachlan, Murrumbidgee and Murray valleys in southern New South Wales. Interestingly, the grains industry in southern New South Wales started the so-called ‘Eight Tonne Club’ (Stapper, 2007), where farmers aim to produce irrigated wheat yields of 8 t ha^{-1} by adopting best management practices (Lacy and Giblin, 2006). The findings from the experiments reported in this paper may well lead to cropping technologies that will underpin a new ‘Twelve Tonne Club’ for farmers in the HRZ of southern Australia. Such yields are not unobtainable, given that the wheat cultivar Amarok used in these experiments is able to yield in excess of 12 t ha^{-1} on the Canterbury Plains of New Zealand (N. Brooks, personnel communication). However, the New Zealand yields are achieved on well-drained soils with irrigation, high levels of N application (300–400 kg N ha^{-1}) and intensive crop protection inputs. Achieving such yields in the HRZ in southern Australia will certainly require crop management practices that make available adequate soil water and nitrogen to the crop plants during the growing season.

The high wheat yields recorded in these field experiments require close examination. The yields were first determined for the area of the raised beds. They were then reduced by adjusting to a total area basis, which included the area of the bed plus the furrow between the beds, assuming that there were no wheat plants growing in the furrow. This was not the case as the furrows were sown to the crop, which did produce grain at maturity albeit at lower yields than that for plants growing on the bed. In fact, our control grain yields of 7.0 and 7.6 t ha^{-1} for the non-lucerne and lucerne sites, respectively (Tables 4 and 5), yielded less than the commercial crop on the remaining part of the paddock which received similar inputs to our control treatments (J. Sheehan, personnel communication). This suggests that our adjusted control yields were a conservative underestimate of the actual yields, by now allowing for grains produced by plants growing in the furrow.

The subsoil amelioration treatments with organic amendments, used in this study, were ambitious. The treatments involved significant mechanical intervention in order to place the high rates (20 t ha^{-1}) of organic amendment at a depth in excess of 30–35 cm, in the upper layers of the B horizon of this soil type. Nevertheless, the results from this intervention were encouraging in producing such large grain yield responses in the average growing season in 2005 (Fig. 1). The bases for the high yields with the organic amendments were the high numbers of wheat kernels produced per unit area. The high yielding plots were able to produce around 25,000–30,000 kernels m^{-2} (Tables 4 and 5). High kernel numbers per unit area are prerequisites for high grain yield (Fischer, 1985) and were achieved in these experiments by combinations of increased ear numbers and grains per ear, compared to the control treatments (Tables 4 and 5). Clearly, the high yielding wheat plants were well supplied with water and nitrogen, enabling this wheat genotype to produce sufficient assimilate at critical stages of growth. This enabled many floret primordia in the developing spikelets to survive and produced kernel during the grain-filling phase.

The organic amendment treatments resulted in marked increases in wheat kernels per m^2 compared to the controls. Increases in the order of 55–60% occurred between the average kernel numbers for the dynamic lifter® and lucerne pellet treatments, and the average numbers for the control and deep-ripped treatment (Table 7). However, the avenue for achieving these increases differed between the two sites. At the higher yielding non-lucerne site, the major part of the increase was achieved by increased ear density (ears m^{-2}), whereas at the lucerne site the increase was achieved equally by higher ear density, spikelet numbers per ear and kernel number per spikelet (Tables 4 and 5). Clearly, different factors were affecting crop growth at the two sites and contributed to these differences in yield and yield component responses. One possible contributing factor was the generally higher nitrogen (N) status in soil at the lucerne site. This was evident in the generally higher N concentrations (Table 6) and shoot N uptake levels prior to anthesis (Table 6). This would have favored tiller initiation and tiller survival across all treatments at this site, thereby diminishing the response in ear density from the organic amendment at this site.

The HI values for the winter wheat cultivar Amarok were remarkably high at the two sites in 2005, with many values exceeding 0.60 (Tables 4 and 5). While values of 0.60 were considered by Austin et al. (1980) to be the upper biological limit for HI, there have been reports of high values of around 0.60 occurring for winter wheat cultivars in the UK (Ruske et al., 2003). In southern Australia however, most field studies report lower HI values for modern wheat cultivars. Yet a number of studies indicate that as the proportion of the crop's water use that is used after anthesis increases, then the HI values also increase (Siddique et al., 1990; Asseng et al., 2001). Several reasons can explain why higher HI values result from greater post-anthesis water use. The first is that any increase in post-anthesis water use would result in more assimilation during the grain-filling period; with more photosynthate moving to the developing grain, increasing the mass of grain produced by the canopy. The second reason is that more post-anthesis water use would tend to prolong the grain-filling period, providing more time for pre-anthesis assimilates to be translocated to the developing grain (Palta et al., 1994). In this study, there were significant rainfall events that occurred on the 16th November and on the 5th December (Fig. 1) which would tend to increase the percentage of the total crop water use occurring after anthesis. An additional explanation for the high HI values might lie in the possibility that some vegetative material, produced early in the growing season, was lost by the time the shoots were harvested at crop maturity, thereby underestimating the denominator in the HI calculation. However, these were no observations made of any senesced shoot material that had fallen to the ground during the cropping cycle. We conclude that the high HI values in this study resulted from the unique combination of the genotype Amarok and the seasonal conditions, which occurred during the 2005 growing season at the two field sites.

4.2. Water and nitrogen considerations

Wheat plants with the deep incorporation of organic amendments were able to extract greater amounts of water below 40 cm during crop growth, compared to those from the control treatment. This was a very advantageous outcome as this subsoil water can be used very efficiently by crop plants. Passioura (1976) points out that this water is accessed late in the growing season, when the products of photosynthesis are being translocated straight to the developing grain, with minimum respiratory losses. Further evidence that highlights the value of subsoil water comes from the results of a recent field experiment in southern New South Wales. In this study, Kirkegaard et al. (2007) were able to show that subsoil water, used by wheat plants after anthesis, resulted in an extra 60 kg of grain yield per ha, for each mm of subsoil water used by the crop, which is 3 times that for total seasonal water use. If subsoil water in this study, which we designate as soil water below 40 cm, was used to produce grain with similar efficiency, then the extra 50 mm of subsoil water used by the organic amendment plants at the non-lucerne site would account for 3 of the 4 t ha^{-1} yield difference, between the organic amendment and the control plants (Table 7). A further striking result from the organic amendment treatment was the change in water extraction patterns of wheat plants. The change was from a pattern where 60% of the profile water at sowing was extracted from the top 40 cm as occurred with control plants at the non-lucerne site and gypsum plants at the lucerne site (Table 7) to that where 60% of the soil water at sowing was extracted from below 40 cm, as occurred with the organic amendment treatments at both sites. This ability to increase the extraction of subsoil water suggests that this approach to subsoil amelioration has the potential to deliver real increases in water use efficiency. Such outcomes are consistent with the views of Turner (2004) who argued that improvements in water use efficiency by crop plants can be achieved if the crop roots are able to extract more soil water from deeper subsoil layers.

In addition to improving water uptake from the subsoil, the organic amendments in this study also increased N supply to the wheat plants. The increased supply resulted in more than a doubling of N uptake during the growth of the crop, when comparisons are made between the average N uptake for the dynamic lifter® and lucerne amendments on the one hand, and the control and deep-ripped treatments on the other (Table 5). The high level of N supply with the organic amendments is also reflected by the high N concentrations in the wheat shoots (Fig. 3), both before and after the rapid growth phase that occurs between stem elongation and anthesis (Fig. 4). There are clear indications from Fig. 3 that the shoots from the control and deep-ripped treatments were low in N, with concentrations at anthesis being less than the critical concentrations of 1.6–1.8% N required for maximum shoot growth at anthesis (Engel and Zubriski, 1982; Mason, 1995) whereas N concentrations in the shoots of the organic amendment were generally above 1.8% N. Given the direct relationship between plant N status and tiller initiation and survival (Spiertz and De Vos, 1983; Salvagiotti and Miralles, 2007), then the higher ear densities with the organic amendment treatments (Tables 4 and 5) can be attributed to the enhanced N status of these plants.

The high kernel numbers per square meter with the organic amendments can also be attributed in part to the high N status of these plants. This is because florets develop during the period between stem elongation and anthesis and any restriction in assimilate supply at this time will reduce the number of fertile florets in each ear (Stockman et al., 1983). This growth stage is also the time when plant growth rate increases as stem extension occurs and so there is internal competition for assimilates between the developing floret primordia and the stems (Kirby, 1988; Mirralles et al., 2000). Given the direct relationship between leaf N status and photosynthetic rate in crop plants (Sinclair and Horie, 1989) then any restriction in N supply prior to anthesis would limit assimilate supply during this critical growth phase, and in turn restrict floret survival, and reduce kernel production by the crop. More direct support for the link between plant N status and kernel numbers per square meter is provided by the results from Abbate et al. (1995). They found that kernel number per square meter was directly related to the N content of wheat ears at anthesis, and suggested that high N content in ears improved floret survival during this pre-anthesis period. Shoot nitrogen concentrations in this study (Fig. 3) suggest that some restriction in N supply was occurring in the control plants prior to anthesis, but not in the shoots of the organic amendment treatments, as discussed above. Furthermore, there were considerably larger increases in shoot N uptake for organic amendment treatments between stem elongation and anthesis, compared to the control plants, which would have limited any N shortage in the shoots for organic amendment treatments. For example, the average increase in N content during this period by shoots from the dynamic lifter® and lucerne pellet treatments around 4 times that for the control and deep-ripped treatments at the non-lucerne site; the equivalent difference between treatment averages was around 3 times at the lucerne site (Table 6). Thus the organic amendments were certainly able to provide N to the wheat plants during this critical growth phase.

The high N status of wheat plants with the organic amendment treatments is further reflected by their high grain protein concentrations at both sites. The plants from these organic amendment treatments were able to produce grain protein percentages in excess of 11.5%, apart from the lucerne + gypsum + MAP treatment at the non-lucerne site (Table 6). This meant that the grain from this high-yielding winter wheat cultivar would meet protein requirements for the Australian Wheat Board (AWB) Australian Hard No. 1 grade. Indeed, the grain from the lucerne amendment treatment at the non-lucerne site with 13.4% protein, would meet the protein requirements for the AWB Australian Hard 13 grade. This is remarkable given the high grain yields of 11–13 t ha^{-1}, and the negative relationship between grain yield and grain protein concentrations that generally occur with wheat (Halloran, 1981). Such relationships infer that the generally finite soil N supply that is taken up by wheat shoots in most cropping situations, is diluted in the developing grain by large amounts of carbohydrate assimilate, that accumulate on the grain in high-yielding situations. This was not the case with the organic amendment treatments in this study. Instead, it is likely that the continuing mineralization of organic N was able to maintain high rates of N supply to the plants over extended periods.

The high grain protein levels in the grain in the organic amendment treatments can be attributed to some extent to the very efficient N remobilization that occurred in the Amarok wheat plants in these field experiments. The NHI values, which are the ratios of grain N to total shoot N at maturity, exceeded 0.92 for the lucerne pellet and dynamic lifter® treatments at both sites (Table 6). The NHI values were also very high for the other treatments, averaging 0.92 and 0.89 across all treatments at the non-lucerne and the lucerne sites, respectively. These values are on the upper end of the range for NHI values in the literature. Stapper (2007) reported values of 0.83–0.86 for irrigated wheat varieties in southern New South Wales, while Flood and Martin (2001) found NHI values for 10 wheat cultivars grown at 3 dryland sites in northwest Victoria range from 0.68 to 0.89, with the lowest values occurring at the driest site. Low values of 0.63–0.68 also occurred at a low rainfall site in Western Australia (Palta and Fillery, 1995). Thus it is apparent that N remobilization from vegetative parts to the wheat grain is dependent on environmental conditions and on plant genotype. It follows that the environmental conditions at Ballan in 2005 were very conducive for N remobilization to occur in Amarok shoots, resulting in these high NHI values.

While the extent of the N remobilization from the canopy parts to the grain was high, there were nevertheless different patterns of N uptake between similar treatments at the two experimental sites. Differences in shoot N uptake between anthesis and crop maturity (Table 6) indicate that there was considerable post-anthesis N uptake for organic amendment treatments at the non-lucerne site, but not at the lucerne site. An average of 131 kg N ha^{-1} was taken up after anthesis by shoots from the dynamic lifter® and lucerne amendment treatments at the non-lucerne site, whereas the average was only 1 kg N ha^{-1} at the lucerne site. On the other hand, the average N uptake for these treatments between stem elongation and anthesis was 96 and 170 kg N ha^{-1} for the non-lucerne and lucerne sites, respectively. The same pattern occurred with average N uptake for the control and deep-ripped treatments at the non-lucerne site, with a more than 3-fold increase in post-anthesis N uptake, compared to that occurring just prior to anthesis (Table 6). However, the amounts of N uptake pre- and post-anthesis were similar for equivalent treatments at the lucerne site. Thus there were real differences in the patterns of N uptake between the two sites. Certainly, one would expect that during the second year of cropping after the 4-year lucerne history, there would be higher levels of plant available and readily mineralisable N in the root zone (Holford, 1981, 1990), compared with the soil at the non-lucerne site, enabling the wheat plants at the former site to take up more N prior to anthesis (Table 6) and generally have higher biomass yields at anthesis (Table 3). The lack of any subsequent post-anthesis N uptake by the wheat plants in the organic amendment treatments at the lucerne site may be due to some negative feedback process that responded to the large amounts of N uptake in the period prior to anthesis, and then resulted in no further N uptake by these plants. Further research is required to determine the reasons for such differences in the patterns of N uptake.

4.3. Extended duration of green leaf area

The deep incorporation of high rates of N-rich organic amendment in the subsoil resulted in maintaining the flag leaf greener for longer. This is perhaps the key to the high grain yields from these treatments. The green flag leaf scores at the hard-dough stage (Fig. 4) show how all organic amendment treatments were able to delay flag leaf senescence and extend the duration of green leaf area during the final stages of the grain-filling period. Observations made at this time indicate that the flag leaves in these treatment plots remained greener than those in the control plots for a period of at least 10 days. The associated yield increases are consistent with research findings where senescence of wheat canopies is delayed. For example, the use of fungicides on high yielding UK wheat crops were able to extend the duration of the flag leaf green area (GFLAD), which in turn increased crop biomass, HI and grain yield (Ruske et al., 2003). The relationships for a range of cultivars between GFLAD and grain yield were linear, even though the rate of yield increase varied between cultivars. The data from Ruske et al. (2003) show that for every extra day that the flag leaf remained green, the grain yield increased by between 84 and 210 kg ha^{-1}. Such yield improvements, associated with delayed senescence and extended green leaf duration during the grain-filling period, are observed with the 'stay green' genetic variants that occur with most crop species (Thomas and Smart, 1993). Spano et al. (2003) were able to produce 'stay green' mutants in durum wheat using a chemical mutagen; these plants produced higher grain yields than their parental lines.

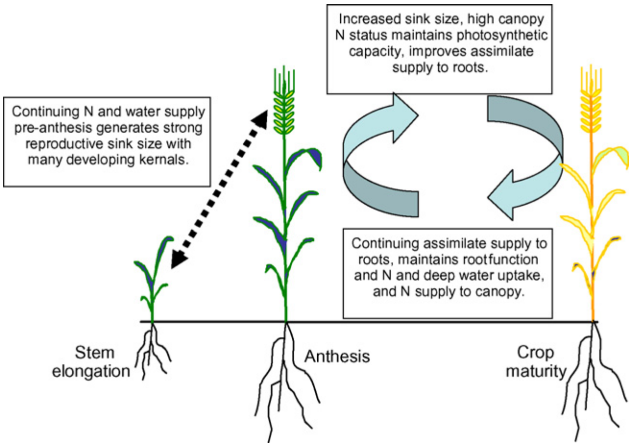

Fig. 5. Proposed schema of the processes that resulted in delayed senescence where organic amendments were incorporated into the subsoil.

In this study, we were able to invoke 'stay green' characteristics in Amorok wheat using organic amendments incorporated in the subsoil. We propose that a series of processes contributed to this outcome and these are outlined in Fig. 5. They all revolve around the provision of: (i) a large and continuing N supply from the organic amendment; (ii) access to deep subsoil water that becomes increasingly available to the wheat plants after anthesis; (iii) a wheat cultivar that was able to respond to the supply of these resources under the seasonal and soil conditions that occurred at the experimental sites at Ballan in 2005.

The first process that led to delayed senescence in the flag leaves involved constructing a large post-anthesis sink strength. This was achieved by generating many large ears with increased spikelet numbers (Tables 4 and 5), which would have been favored by the high N and adequate soil water supply during the crop tillering process. Continuing N supply, together with an adequate photothermal quotient prior to anthesis would have resulted in floret development and survival and led to the large numbers of developing kernels per square meter (Tables 4 and 5). Continuing photosynthesis in turn provides assimilate to the developing kernels and to the roots. Root assimilate supply invokes the third process. This is where the roots are then able to maintain their capacity to take up additional N for the developing grain and the flag leaves. Borrell et al. (2001) point out how N uptake during grain-filling in sorghum was directly correlated with grain number per square meter, indicating that sink demand is able to directly influence N uptake during grain-filling. This continuing N uptake is able to maintain N concentrations in flag leaves, which in turn delay senescence and prolong green leaf area (Borrell et al., 2001). The processes outlined above are consistent with the suggestions of Richards (2000) for increasing wheat yields in the future. They are also consistent with the results of Pan et al. (1995) where increases in sink strength in high yielding maize hybrids were able to sustain photosynthesis and N accumulation during the grain-filling period.

The importance of the cultivar Amarok cannot be overlooked in understanding how organic amendments were able to delay flag leaf senescence. This genotype was able to respond to the favorable pre-anthesis growing conditions and produce many large ears, with many spikelets, containing competent florets that developed into kernels (Tables 4 and 5). This capacity to respond is genotype dependent. For example, Mi et al. (2000) found that their LZ953 wheat cultivar was able to produce large spikes with large kernel numbers when supplied with a continuing N supply. This cultivar was then able to increase and continue post-anthesis N uptake and delay leaf senescence, in comparison to their second LM14 cultivar. This genotype could only produce smaller spikes with fewer kernels than LZ953; it took up less N after anthesis and displayed an accelerated senescence compared with LZ953.

The important finding from the study by Mi et al. (2000) relates to the N supply to the wheat plants. The extended duration of green leaf area only occurred when the responsive LZ953 cultivar received continuing N inputs at sowing, stem elongation and at anthesis. This ensured that there was sufficient available N in the soil to enable additional continuing N uptake to occur in response to the increased sink demand. The continuing N supply from the mineralizing organic amendment would appear to ensure that this condition prevailed during the grain-filling period, while the additional subsoil water ensured that this available subsoil N could be taken up by the wheat roots.

4.4. Impact of the lucerne history

An unexpected result from this study was the lower yield of Amarok wheat at the lucerne site compared to the non-lucerne site, when organic amendments were incorporated in the subsoil. Caution needs to be exercised in this comparison as the two sites, although similar in general properties (Table 1), were in adjacent paddocks, and located 70 m apart. Nevertheless, the expectation was that the 4 years of lucerne from 1999 to 2003 would have a beneficial effect on crop yield, such that grain yields in the second crop following the lucerne phase would be at least equal to, or indeed higher than the adjacent crop in the non-lucerne paddock, that had been cropped continuously for 8 years. In fact lucerne growth, with associated development of deep root channels penetrating the B horizon of the duplex soil, was considered to be a key tool in the amelioration of the dense sodic subsoils at the Ballan site. Numerous authors have discussed this possibility (Qadir and Osster, 2002; Ilyas et al., 1993; Cresswell and Kirkegaard, 1995). However, it appears that the yields, with the organic amendments, were not increased by the 4-year lucerne history. Instead there appeared to be a reduction in yield with the lucerne history.

Wheat growth at the lucerne site, with organic amendments, was actually superior to that at the non-lucerne site prior to anthesis. The former plants had higher biomass yields (Table 2) and these had higher N contents (Table 6) than equivalent plants at the non-lucerne site. However, between anthesis and crop maturity, there was some restriction in the growth of these plants at the lucerne site. Minimal N uptake occurred during this period (Table 6), fewer spikelets developed on the smaller number of fertile ears, resulting in fewer kernels per square meter, and grain yields were lower by an average of 1.8 t ha^{-1} when averaged out over the 3 organic amendment treatments (Tables 3 and 4). It is unlikely that there was a post-anthesis limitation in N supply at the lucerne site as shoot N concentrations were consistently higher at the hard-dough stage at this site (Fig. 3). One explanation for this lack of response in grain-filling at the lucerne site may relate to the greater N uptake and growth prior to anthesis at this site, resulting in fewer resources being available for grain-filling after anthesis. Deep soil water may have been one of these resources. There were larger losses of soil water from the deeper 40–60 and the 60–80 cm layers in the soil for the control treatment at the lucerne site, compared to the non-lucerne site (Table 7), between sowing and crop maturity. This may have resulted from increased earlier growth of wheat roots down into the deeper soil layers before anthesis through old lucerne channels, resulting in more soil water being used from these deeper soil layers before anthesis, rather than after anthesis. The lower HI values for the control treatments at the lucerne site (Table 5), compared to the non-lucerne site (Table 4) are consistent with this proposition, according to the discussion relating to HI values above. These explanations will be further tested in the next paper in this series, which will present root growth data and water extraction patterns.

4.5. Agronomic considerations

The marked increases in grain yield that occurred with the deep incorporation of organic amendments indicate that this approach has potential to increase crop productivity. The current recommendations that farmers would use to improve the dense sodic subsoils, involving deep ripping and alleviating the sodicity with gypsum (Jayawardane and Chan, 1994), proved ineffective in this study. Whereas deep ripping temporarily decreases bulk density and gypsum enhances soil aggregation at the domain level, organic amendments have been shown to increase and stabilize macro-aggregates of this dense sodic subsoil (Clark et al., 2007). However, there are a number of issues raised by these results that will need resolution before any widespread use of deep organic amendments can be considered. These include the form of the yield response curve to increasing amounts of organic amendment, the cost-effectiveness of different types of amendments with respect to N content, and the residual effects of organic amendments on the yields of a series of following crops. Machinery issues arise as to the implements that will be required to place large quantities of organic material at depth, the timing of the placement, and whether the material should be grown *in situ* and buried, or imported onto the farm and incorporated into the subsoil. Finally, there is the issue of crop genotype and whether other crop species, or indeed wheat cultivars, would respond in a similar manner to Amorok wheat. Field experiments are currently underway to address these issues.

One contributing factor to the high wheat yields with organic amendments was the deep soil water that the wheat plants were able to access at the Ballan site. Previously, this deep subsoil water could not be extracted by crop roots and so the deeper subsoil layers remained permanently moist during cropping cycles. In this study, there was considerable extraction of this water when organic amendments were incorporated in the subsoil (Fig. 5). Angus and van Herwaarden (2001) question whether this deep water, that is used as a result of changed management, will be replenished by rainfall in the following year, or whether it might take several years to be replenished. If the latter is the case then the potential to maintain large yield responses in successive crops following the incorporation of organic amendment in the subsoil, will diminish. Our current observations of soil water in the profiles at the Ballan site suggest that the dry subsoil in the organic amendment plots following the 2005 crop has encouraged deep rainfall infiltration and that water replenishment in the subsoil will occur in an average rainfall year. This needs to be confirmed with future field studies.

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