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Crop responses to subsoil manuring. I. Results in south-western Victoria from 2009 to 2012

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Abstract. Subsoil manuring is a practice that involves placing high rates of organic amendments in bands at the base of rip-lines that extend down into the subsoil to a depth of 30–40 cm, in order to ameliorate poorly structured clay subsoils. The objective of this study was to determine whether the increases in crop yield from this practice, which occurred at one site in the high-rainfall zone in Victoria from 2005 to 2007, would occur at other sites and in other seasons in south-western Victoria. On-farm field experiments were therefore carried out at three sites in south-western Victoria between 2009 and 2012 to measure the yield responses to subsoil manuring. The study found that subsoil manuring with poultry litter resulted in consistent and recurring increases in estimated grain yield at these sites, with responses occurring with consecutive crops. Increases in estimated grain yield continued for 4 years, with average increases in hand-harvested yield of 3.5 t ha^{-1} for wheat, 1.6 t ha^{-1} for canola and 2.3 t ha^{-1} for faba beans. The estimated increases in grain yield were frequently associated with the increased extraction of deep subsoil water after anthesis. A treatment involving deep-banded nitrogen (N) and phosphorus (P) fertilisers and additional in-crop N, which matched the N and P in the poultry litter, yielded less than the full rate of subsoil manuring in seven of the eight site-years. This suggests that yield responses from subsoil manuring were not solely due to the release of N and P from the deep-banded poultry litter.

Additional keywords: dense clay, duplex soil, impermeable, sodicity, subsoil constraints.

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Introduction

The high-rainfall zone in Victoria, with annual rainfall in excess of 500 mm, has become an important grain-growing region. The higher rainfall and longer growing season increases the potential for higher crop yields compared with the low- and medium-rainfall regions of the wheatbelt (Zhang *et al*. 2006; Riffkin *et al*. 2012). Many of the soils in the region have lighter textured topsoil overlying dense clay subsoils with bulk densities averaging 1.5–1.6 g cm^{-3} (MacEwan *et al*. 2010). The dense clay subsoils are a major soil constraint that limits the realisation of crop yield potential in this high-rainfall cropping region.

There are several problems with these dense clay subsoils. The first is the limited supply of plant-available water above permanent wilting point, due to the scarcity of water storage pores of diameter 0.5–50 μm (Topp and Davis 1985). Then as the subsoil becomes moist, the scarcity of larger transmission pores with diameters >50 μm restricts oxygen diffusion to the respiring roots in the subsoil and curtails root function (MacEwan *et al*. 2010). In addition, the impermeable clay can impede drainage, resulting in waterlogging in wet winters when rainfall exceeds evaporation (Gardner *et al*. 1992); this restricts crop growth and frequently limits final yield. The combination of the clay texture and the high bulk density means that restricted pore space is problematic for crop roots. This situation is exacerbated when the clay is dispersive, due to the abundance of exchangeable sodium and other dispersive cations (Rengasamy and Olsson 1991). The dispersed clay particles, and the potential for increased swelling of the clay, can result in physical blockage of larger pores in the clay matrix, further restricting pore space and permeability (So and Aylmore 1993). It is therefore not surprising that crop yields in the region frequently do not exceed one-third of their water-limited yield potential (Riffkin and McNeill 2006).

A subsoil amelioration practice known as subsoil manuring (Gill *et al*. 2009) has been developed at Ballan, in south-western Victoria, to overcome these subsoil constraints. It involves the incorporation of high rates of up to 20 t fresh weight ha^{-1} of a nutrient-rich organic amendment in rip-lines spaced 80 cm apart, at depths of 30–40 cm in the upper layers of the clay subsoil. This subsoiling intervention first occurred in April 2005, and a long-season winter wheat (*Triticum aestivum* L.) was sown in the plots in the first week of May. Wheat yields of 11–13 t ha^{-1} occurred on these subsoil-manured plots, compared with 7–8 t ha^{-1} on the control and deep-ripped plots (Gill *et al*. 2008). The large yield response by the first crop following the subsoil treatment is important, given the high costs involved with the practice.

Large increases in yield, in the order of 55–60% above the yield of the control, followed with the wheat crop in 2006 and a canola (*Brassica napus* L.) crop in 2007 (Gill *et al*. 2012). The subsoil-manured crops were able to extract more water from the subsoil during the post-anthesis period than the control crops. The treated subsoils were then able to capture and store water in the dry subsoil from subsequent rainfall events, and this water could then be used by the following crop (Gill *et al*. 2012). The improved capture and storage of rain in the subsoil was attributed to increases in the macroporosity and saturated hydraulic conductivity in the subsoil, which occurred during the first cropping cycle in 2005 (Gill *et al*. 2009). Macroporosity in the amended clay subsoil more than doubled, while the saturated hydraulic conductivity in the clay increased >50-fold. These positive changes in physical properties closely correlated with increased root growth in the amended layer, and with the yields of the crop that grew on the treated plots. The nitrogen (N) status of subsoil-manured crops also increased in response to the extra 500–700 kg of total N ha^{-1} added in the amendments. Nitrogen uptake at maturity increased 2-fold, with a 40% increase in grain protein concentration relative to control plants (Gill *et al*. 2008). The authors attributed the crop responses to subsoil manuring at Ballan to the increased supply of water and nutrients in the subsoil, which became available when crop roots were able to grow in the amended layer.

Similar work to the Ballan study has been conducted in south-western Victoria, and in the Upper North of South Australia, from 2014 to 2016 (Celestina *et al*. 2018). That study set out to determine whether yield responses to subsoil manuring resulted from the amelioration of subsoil constraints, which would then result in an increased supply of subsoil water to the crop, or whether the responses resulted from the extra nutrients supplied in the organic amendment. Results from seven field trials indicated that, under the conditions prevailing at these sites during the study, the key factor driving crop yield responses to subsoil manuring was crop nutrition, particularly N, supplied in the amendment. They found no consistent evidence that yield responses resulted from the amelioration of subsoil constraints. However, physical properties were not measured in the subsoils before or after subsoil manuring took place, and few yield responses were reported.

Although the basis for the yield responses are unclear, the practice of subsoil manuring does appear to be a promising management practice for increasing crop productivity on these soils with dense clay subsoils, in the high-rainfall zone. Although the results at Ballan from 2005 to 2007 were impressive, they only relate to three crops at one site. If this practice is to have industry application, then it will need to deliver consistent yield increases at other sites in the high-rainfall zone, and these need to occur across a range of seasons.

The present paper documents the results from subsoil manuring at three new experimental sites in south-western Victoria from 2009 to 2012. Four successive crops were grown over four growing seasons at two sites, and three crops were grown at the third site. The field experiments tested two hypotheses. The first was that subsoil manuring would increase crop yield on a range of soils with dense clay subsoils in the Victorian high-rainfall zone, similar to those reported at Ballan between 2005 and 2007 (Gill *et al*. 2008, 2012). The second hypothesis was that yield responses to subsoil manuring result from the nutrients, principally N, added in the organic amendment. The experiments were conducted in cropping paddocks and compared the effects of subsoil treatments on the performance of successive crops in the crop rotation.

Materials and methods

Site selection

Three field experiments were established in cropping paddocks on farms in the high-rainfall cropping zone of south-western Victoria. The soils in the paddocks were identified by farmers as having dense clay subsoils where crop yields were reduced in years with dry finishes. One site was on a farm near Penshurst (37.77°S, 142.23°E), and a second to the north-east of Derrinallum (37.93°S, 143.27°E). The third site was north of Wickliffe (37.70°S, 142.70°E). All paddocks had a history of continuous cropping in a cereal–canola rotation for at least 10 years before the experiments began.

Sites at Penshurst and Derrinallum were established in April 2009, whereas the Wickliffe site was established in late March 2010. Yield measurements were undertaken for successive crops at Penshurst and Derrinallum from 2009 to 2012, and for crops at Wickliffe from 2010 to 2012. Neutron-probe access tubes were placed in all of the plots in 2010 and enabled soil-water measurements to be made from 2010 to 2012. Soil samples collected from the three profiles were analysed, and selected soil properties are presented for different depths at the three sites (Table 1). Exchangeable sodium percentages in the clay subsoil indicate that the soils at Derrinallum and Wickliffe were Sodosols with dispersive subsoils, whereas the soil at Penshurst was a Chromosol (Isbell 2002).

Rainfall records at nearby weather recording stations operated by the Bureau of Meteorology provided annual, seasonal and April–November growing-season rainfall totals for 2009–12 for each site (Table 2). The records encompassed periods of 132, 58 and 135 years for the Penshurst, Derrinallum and Wickliffe sites, respectively. Rainfall totals for each year of the rainfall record were sorted on increasing rainfall and divided into 10 decile bands, enabling the decile ranking for each rainfall total in the 2009–12 period to be determined for each site (Table 2).

Experimental design and treatments

Each field experiment had six treatments that were randomly allocated to each of four blocks in a randomised complete block design. Each experimental plot comprised two 2-m-wide adjacent raised beds 10 m in length. The treatments involved an untreated control and a deep-ripped control, and four treatments with different materials incorporated in bands in the subsoil: two treatments with poultry litter (full and half rate), a treatment with matched N and phosphorus (P) fertiliser

Table 1. Soil types and selected soil properties at different depths at the three experimental sites in south-western Victoria
EC, Electrical conductivity measured in 1 : 5 water suspension. Chemical methods used are described in Rayment and Higginson (1992). Soil texture was measured with a Mastersizer 2000 particle size analyser (Malvern Panalytical, Malvern, UK)

Experimental site	Soil Order	Depth (cm)	pH ($CaCl_2$)	EC (dS m^{-1})	Exch. cations (cmol kg^{-1}) Ca	Mg	K	Na	Exch. Na percentage (%)	Total C (g kg^{-1})	Total N	Clay	Silt (%)	Sand
Penshurst	Chromosol	0–10	5.57	0.11	11.48	6.24	0.81	0.27	1.4	40.3	3.3	35.3	18.0	46.7
		10–30	6.06	0.06	6.65	6.36	0.36	0.47	3.4	23.0	1.7	43.7	20.3	36.0
		30–50	6.05	0.06	6.00	6.43	0.35	0.57	3.9	21.1	1.6	44.5	20.1	35.4
Derrinallum	Sodosol	0–10	5.81	0.11	6.77	3.76	0.45	0.44	3.8	23.5	1.9	36.9	18.8	44.3
		10–30	6.49	0.09	5.23	7.77	0.42	1.92	12.3	9.5	0.8	44.9	20.7	34.4
		30–50	6.80	0.11	5.57	8.55	0.45	2.30	13.6	10.3	0.9	49.0	18.6	32.4
Wickliffe	Sodosol	0–10	5.75	0.09	5.40	1.16	0.68	0.42	5.5	21.1	2.0	31.5	22.7	45.8
		10–30	6.63	0.06	2.94	2.18	0.37	0.84	13.6	8.1	0.9	36.2	20.5	43.3
		30–50	6.74	0.08	4.27	4.89	0.57	1.64	14.4	8.3	0.9	43.8	19.1	37.1

Table 2. Annual, seasonal and growing-season (April–November) rainfall (mm), and their decile rankings (in parentheses), at the three experimental sites from 2009 to 2012
LTA, Long-term average

Experimental site	LTA (mm $year^{-1}$)	Year	Annual rainfall	Seasonal rainfall Summer	Autumn	Winter	Spring	Growing season rainfall
Penshurst	718	2009	646 (3.3)	100 (4.4)	158 (4.4)	253 (6.4)	187 (4.8)	541 (4.9)
		2010	867 (9.3)	137 (7.1)	184 (6.5)	279 (7.7)	215 (6.5)	632 (7.8)
		2011	780 (7.0)	244 (9.8)	216 (8.3)	233 (5.2)	153 (2.6)	538 (4.7)
		2012	723 (5.4)	114 (5.7)	177 (5.9)	297 (8.5)	136 (1.9)	545 (5.2)
Derrinallum	647	2009	595 (3.8)	92 (3.1)	109 (2.5)	224 (7.2)	208 (6.8)	499 (5.8)
		2010	929 (9.8)	187 (8.8)	161 (6.4)	287 (10.0)	242 (8.8)	633 (8.9)
		2011	645 (5.2)	312 (10.0)	148 (5.8)	145 (1.6)	130 (1.6)	384 (1.5)
		2012	577 (3.5)	39 (0.1)	158 (6.2)	200 (5.8)	156 (3.2)	464 (4.8)
Wickliffe	558	2010	802 (9.9)	113 (6.6)	132 (5.6)	256 (9.8)	237 (9.5)	572 (9.3)
		2011	618 (7.9)	268 (10.0)	156 (7.4)	134 (2.5)	133 (3.3)	357 (2.3)
		2012	477 (2.5)	53 (1.6)	127 (4.9)	183 (6.6)	124 (2.6)	402 (4.3)

nutrients, and a combination treatment with both poultry litter and fertiliser nutrients (Table 3). The full rate of subsoil manuring involved the addition of 20 t fresh weight of poultry litter per ha (16.4 t ha^{-1} dry weight) in bands at a depth of 30–40 cm in the subsoil. The litter had a moisture concentration of 18% and contained 38 g N, 18 g P and 20 g potassium (K) kg^{-1} on a dry-weight basis.

The subsoil amendments were added manually through 20-cm-diameter pipes attached behind large ripper shanks, and formed continuous bands of amendment at a depth of 30–40 cm at the base of the rip-line. In each 2-m-wide raised bed, there were two rip-lines running the length of the bed and spaced 80 cm apart on either side of the centre. This intervention took place in late March. The deep-ripping brought large, dry clods to the soil surface, but these were subsequently broken down by passes with the rear wheels of the tractor, by the rain that fell in April, and by surface tillage when necessary. The April rain at the three sites amounted to two or three rainfall events, with each event totalling 6–25 mm over periods of 1–4 days. This ensured that the surface soil of the ripped plots had a satisfactory tilth, enabling the crop to emerge successfully across the plots in late autumn.

The fertiliser treatment matched the N and P nutrients added in the full rate of poultry litter. It involved adding 295 kg P ha^{-1} as diammonium phosphate and 70 kg K ha^{-1} as K_2SO_4 to the base of rip-lines. These fertilisers added the equivalent of the P and a portion of the K contained in the poultry litter. The balance of the N required to match the total N in the poultry litter was topdressed, by adding 179 kg N ha^{-1} as urea during late vegetative growth in the first and second years. Split N

Table 3. Experimental treatments, and amounts of nitrogen (N) and phosphorus (P) added in amendments
DAP, Diammonium phosphate

Treatment description	Nutrients in amendments (kg ha^{-1}) N	P
Control	Nil	Nil
Deep-ripped	Nil	Nil
Full rate subsoil manuring: fresh weight poultry litter, 20 t ha^{-1}	623	295
Half rate subsoil manuring: fresh weight poultry litter, 10 t ha^{-1}	311	148
N and P added as urea and DAP to match full subsoil manuring	623	295
Mixed: half rate of N and P plus half rate of subsoil manuring	623	295

applications were carried out to mimic the continuing supply of N from the organic amendments and to avoid any toxicity effects from adding all of the soluble N fertiliser upfront in the amendment band.

Crop growing conditions

The crops planted in each year of the trial were the same as those established by the grower in the broader farm paddock. At Penshurst, canola crops were sown during late April–early May, with wheat crops being sown after the canola. The crop sequence from 2009 to 2012 at Penshurst was wheat (cv. Sentinel), canola (cv. Thumper), wheat (cv. Bolac) and canola (cv. Thumper). The sequence and sowing dates at Derrinallum were wheat (cv. Derrimut sown 23 May), canola (cv. Pioneer 46Y83 sown 16 May), wheat (cv. Bolac sown 9 May) and wheat (cv. Lincoln sown 1 June). The sequence at Wickliffe during 2010–12 was wheat (cv. Revenue sown 19 April), wheat (cv. Revenue sown 30 April) and faba beans (*Vicia faba* L. cv. Farah sown 27 May). Weeds, pests and diseases in the crops were managed by the same pesticide inputs that protected the crops on the farm. Each crop grown on the experimental plots received the same weed and pest management as in the surrounding paddock for that year.

All crops were sown on the 2-m-wide raised beds (furrow to furrow) at each of the three sites, with each plot containing two adjacent beds that were 10 m long. Wheat and canola were sown in rows 25 cm apart such that there were seven rows across the top of the beds; the faba beans at Wickliffe were sown in rows 40 cm apart. Wheat crops were sown at 70–75 kg seed ha^{-1} and canola crops at 3–4 kg seed ha^{-1}. The faba bean crop at Wickliffe was sown at 130 kg seed ha^{-1}. Standard fertiliser applications to the commercial crop were also applied to the experimental plots and were additional to the nutrients in the treatments. These generally involved monoammonium phosphate at 70–90 kg ha^{-1} applied with the seed, and topdressed urea at 50–100 kg N ha^{-1} applied towards the end of the tillering phase, or around the flower-bud stage for the canola crops. The wheat crop at the Wickliffe site in 2010 received three applications of topdressed urea before the booting stage, totalling 115 kg N ha^{-1}, owing to the above-average spring rainfall.

There were two site-years when crops failed to establish. The first was at Derrinallum in 2010 when 287 mm of rain fell between June and August, making that winter the wettest in 58 years of records, and the canola crop in 2010 failed to establish successfully. The second crop lost was the wheat crop at Wickliffe in 2011, which was overrun by herbicide-resistant annual ryegrass.

Measurements

Crop yield and grain quality

Grain yields were measured at crop maturity using a stratified quadrat sampling procedure. The procedure enabled rapid, low-cost estimates of yield from replicated plots at sites that spanned a distance of 500 km. This sampling needed to occur rapidly, because growers were keen to harvest the mature crops in which the trials were located. The sampling involved removing all mature plants at ground level from five random quadrats (20 cm by 50 cm) in one raised bed of each plot, with each quadrat covering one 50-cm length of row. The location of each quadrat was identified by throwing a ruler along the target row, and positioning the quadrat at the landing point.

In order to avoid border-edge effects, which can increase yields from extra solar radiation and soil moisture, no quadrat cuts were made from the outside border rows 1 and 7 on the bed (Rebetzke *et al*. 2014; Fischer 2015). One quadrat was cut from row 2 and one from row 6. Both of these rows were 10 cm from the rip-line containing the poultry litter. The remaining three quadrats were taken randomly along the central row 4, which was 40 cm from the rip-line. The average distance of the sampled rows from the rip-line was 28 cm, whereas the distance averaged across every row from 2 to 6 was 18 cm. Thus, the sampling procedure avoided over-sampling of plants that were close to the rip-line containing the litter band; this was done as a precaution in case these plants yielded differently from plants more distant from the rip-line. No visual increases in shoot growth were apparent in rows closest to the rip-line, compared with the central rows, in these field experiments.

Mature fertile tillers of wheat were bulked and mixed, and the total number of ears was counted and total biomass measured. A subsample of 10 mature tillers was randomly selected; these tillers were weighed, and the grain was separated, weighed and counted. This enabled an estimate of air-dried mature grain yield to be calculated. Yield components and harvest index were also determined from the subsample of harvested plants. The N concentration in the grain was measured by using a Vario EL analyser (Elementar, Langenselbold, Germany) and multiplied by 6.25 to give the grain protein concentration. Estimates of canola and faba bean yields were determined in a similar manner; oil and protein concentrations were not measured in the canola or faba bean seed.

The accuracy of this harvesting process for the different crops was assessed by comparing the grain yield from the non-ripped control plots with the farmers' records of the total grain yield from the commercial crops in respective paddocks. The two measures of crop yield were consistent, with minimal differences between the yield measurements for the control treatment and the paddock in each case. Although these yields were similar, this rapid-harvesting protocol would have been more accurate and convincing if there were more quadrats per plot, with all grain from all harvested ears contributing to the yield. We use the term 'estimated yield' throughout this paper to reflect the limitations of the harvest protocol.

Soil-water extraction from the subsoil

The volumetric water content in the 20–100 cm soil layer was measured in successive 20-cm increments by using a neutron probe (Luebs *et al*. 1968). These measurements were made from 2010 to 2012, with access tubes installed in the middle of the bed, midway between the original rip-lines, in the second 10-m-long raised bed in each plot, which was not used for yield determination. The neutron probe was calibrated from the relationship between probe readings and volumetric water content (θv) in each 20-cm soil layer, to a depth of 1 m. This was determined for a well-watered soil profile and a moderately dry profile. Soil columns were removed from both profiles to install access tubes for probe readings and for measuring θv in the soil layers. Soil samples from the topsoil layers (0–20 cm) were collected at the same time as neutron probe measurements were made, and the water content in the sample was determined gravimetrically following drying in the laboratory at 105°C and converted to volumetric water content (mm) by using pre-determined bulk densities. Differences in soil-water content between anthesis and crop maturity were calculated for each plot.

Statistical analyses

Analysis of variance was performed on the data for estimated grain yields, protein concentrations in wheat grains, wheat yield components, wheat harvest indices, and the differences in subsoil water between anthesis and maturity for each crop by using GENSTAT 5th Edition (Lawes Agricultural Trust, Hemel Hempstead, UK). Data were checked for normality and for homogeneity of variance before analysis to determine whether data transformations were required. No transformations were required. The l.s.d. values at $P = 0.05$ were computed to compare treatment means when significance ($P \leq 0.05$) was detected from F-tests in the analysis of variance.

Results

Penshurst

The full rate of subsoil manuring (20 t poultry litter ha^{-1} in the subsoil) resulted in large and consistent increases in estimated grain yield over the four crops grown at the Penshurst site from 2009 to 2012 (Table 4). Increases in estimated wheat yield ranged from 2.8 to 4.5 t ha^{-1}, and canola yield increases ranged from 1.2 to 2.0 t ha^{-1}. In 2009, the grain protein concentration of wheat also increased significantly in the crop with the full rate of subsoil manuring. There was considerable waterlogging damage in the canola crop at Penshurst in 2010 following a very wet period in August and early September, when >160 mm fell in five rainfall events. The raised beds in a portion of the experimental area were unable to shed excess surface water. This resulted in variable plant mortality across the plots and meant that no significant differences ($P = 0.93$) in estimated yield were detected between treatments (Table 4).

The half rate of subsoil manuring (10 t ha^{-1} of incorporated poultry litter) also significantly increased estimated wheat yields in 2009 and 2011 (Table 4), but the magnitude of increase, 2.0–3.2 t ha^{-1}, was smaller than for the full rate. The half rate of subsoil manuring did not increase estimated canola yields in 2010 and 2012, nor did it significantly increase grain protein concentrations of wheat in 2009 or 2011.

The full rate of matched fertiliser N and P had minimal effects on estimated grain yield at this site (Table 4). The treatment did not increase grain yield above that of the control for any of the four crops during 2009–12. It produced significantly lower estimated grain yields than the full rate of subsoil manuring in 2009, 2011 and 2012, and lower yields than the half rate of subsoil manuring in 2011 and 2012. However, it did result in grain protein concentrations for the wheat crops in 2009 and 2011 being similar to those with the full rate of subsoil manuring; grain protein concentration was not significantly greater than in the control in 2011. The mixed treatment with poultry litter and fertiliser nutrients also failed to increase estimated crop yields, except for the final canola crop in 2012 when this treatment produced a yield similar to the half rate of subsoil manuring. Deep ripping alone did not increase estimated grain yield for any of the crops at Penshurst (Table 4), nor did it have any beneficial effect on estimated yields at other sites (see below).

Derrinallum

Crop responses to the subsoil treatments on the Sodosol at Derrinallum from 2009 to 2012 were generally similar to those on the Chromosol at Penshurst. The full rate of subsoil manuring in 2009 resulted in a large response in the wheat crop, producing an extra 4.8 t ha^{-1} of estimated yield (Table 5), almost double the yield estimate of the control. Subsequent increases in estimated yield were 2.4 t ha^{-1} in 2011 and 4.1 t ha^{-1} in 2012. There were no significant increases in protein concentration of wheat grain above the control for the full rate of subsoil manuring or for any other treatment, for the three wheat crops at Derrinallum. The half rate of subsoil manuring produced additional wheat yields of 1.9–2.7 t ha^{-1} from 2009 to 2012, representing significant increases in estimated yields of ~40–50% above the control. These increases in estimated yield were significantly less than those for the full rate of subsoil manuring in 2009 and 2012, but not in 2011.

The matched N and P fertiliser nutrients generally performed better at the Derrinallum site than at Penshurst. The treatment resulted in significant increases in estimated yield above the control for the three wheat crops between 2009 and 2012. The increases ranged from 1.6 to 2.3 t ha^{-1}, and were significantly smaller than the increases resulting from the full rate of subsoil manuring in 2009 and 2012, and smaller than the increase for the half rate of subsoil manuring in 2012 (Table 5). The full rate

Table 4. Estimated grain yields and grain protein concentrations of wheat for treatments at Penshurst, 2009–12

Estimated grain yields were determined by hand-harvested, stratified quadrat sampling procedure (see *Materials and methods*). n.a., Not available

Treatment	Estimated grain yields (t ha^{-1})				Grain protein (%)	
	2009 wheat	2010 canola	2011 wheat	2012 canola	2009 wheat	2011 wheat
Control	4.8	0.8	6.8	2.3	13.3	9.3
Deep-ripped	4.5	1.2	7.4	2.0	13.3	9.6
Full rate subsoil manuring	7.6	2.0	11.3	4.3	15.8	10.7
Half rate subsoil manuring	6.8	1.4	10.0	2.9	13.6	10.0
Matched fertiliser nutrients	6.0	1.3	7.7	1.9	15.8	10.6
Mixed fertiliser and subsoil manuring	5.7	1.2	6.8	3.2	15.7	10.8
l.s.d. ($P = 0.05$)	1.6	–	2.1	0.7	n.a.	–
P-value	0.001	>0.05	0.001	0.02	0.007	>0.05

Table 5. Estimated grain yields and grain protein concentrations of wheat grown at Derrinallum, 2009, 2011 and 2012

Treatment	Estimated grain yields (t ha^{-1})			Grain protein (%)		
	2009 wheat	2011 wheat	2012 wheat	2009 wheat	2011 wheat	2012 wheat
Control	5.0	5.0	6.3	11.5	10.3	10.6
Deep-ripped	6.4	5.5	6.9	11.7	11.0	11.3
Full rate subsoil manuring	9.8	7.4	10.4	12.9	11.6	10.6
Half rate subsoil manuring	7.7	6.9	8.8	12.1	10.9	11.3
Matched fertiliser nutrients	7.1	7.3	7.9	12.7	13.0	11.9
Mixed fertiliser and subsoil manuring	8.8	7.1	8.8	12.7	11.4	11.3
l.s.d. (P = 0.05)	1.6	1.8	1.1	–	–	–
P-values	0.001	0.046	0.001	>0.05	>0.05	>0.05

of fertiliser nutrients also resulted in the highest grain protein concentrations of wheat in 2011 and 2012, but these did not differ significantly from the control. The mixed treatment with the half rates of nutrients and poultry litter performed quite well at Derrinallum, producing estimated yield increases generally similar to the half rate of subsoil manuring (Table 5).

Wickliffe

The first crop grown after treatment imposition at the Wickliffe site in 2010 encountered the very wet La Niña year (Bureau of Meteorology 2018). Winter, spring, growing season and annual rainfall totals for 2011 were all in the 9–10 decile bands (Table 2). Wheat yielded ~9 t ha^{-1} for the control and the deep-ripped treatments. All subsoil-manuring treatments (full rate, half rate, mixed with fertiliser nutrients) resulted in significant increases in estimated wheat yield of >2 t ha^{-1} above the control treatments. The full rate of fertiliser N and P performed poorly in 2010, with an estimated yield not significantly (P > 0.05) greater than the control, and it produced significantly lower yields than other full rate and the half rate subsoil manuring treatments.

No crop was harvested at Wickliffe in 2011; however, a crop of faba beans was grown successfully at the site in 2012. For this crop, the full rate and the half rate of subsoil manuring resulted in similar significant increases in estimated yield of 2.7 and 2.6 t ha^{-1}, respectively, above the control (Table 6). Subsoil treatment involving either the full or half rate of fertiliser nutrients did not result in any significant increase in estimated faba bean yield above the control in 2012.

Extraction of subsoil water

Increases in estimated yields with the full rate of subsoil manuring were generally associated with significantly larger net decreases in water content in the deep (50–100 cm) subsoil layer between anthesis and crop maturity compared with the control treatment (Table 7). We assume that these net decreases in water content were due to the extraction of this subsoil water by the crop. These larger volumes of extracted subsoil water with the full rate of subsoil manuring relative to the control occurred for five of the seven crops grown between 2010 and 2012 (significant for four crops). Water extraction with the full rate of subsoil manuring was significantly (P < 0.05) greater than with all other treatments for the wheat crops at Penshurst in 2011 and Derrinallum in 2012, and there was a trend (P = 0.06) for this to occur with the canola crop at Penshurst in 2012.

Table 6. Estimated grain yields of wheat and faba beans and grain protein concentrations of wheat grown at Wickliffe, 2010 and 2012

Treatments	Estimated grain yields (t ha^{-1})		Grain protein (%)
	2010 wheat	2012 faba beans	2010 wheat
Control	9.1	3.6	9.3
Deep-ripped	8.6	4.0	9.6
Full rate subsoil manuring	11.6	6.3	10.7
Half rate subsoil manuring	12.0	6.2	10.0
Matched fertiliser nutrients	9.3	4.5	10.6
Mixed fertiliser and subsoil manuring	11.3	5.0	10.8
l.s.d. (P = 0.05)	1.7	1.5	–
P-values	0.002	0.007	>0.05

By contrast, generally there were no significant increases in water extraction from the subsoil layer with the other treatments relative to the control, apart from the half-rate of subsoil manuring and the fertiliser treatment for the canola crop at Penshurst in 2010. There were no significant differences in water extraction from the subsoil between treatments at Derrinallum in 2011.

Changes in subsoil water content during the latter half of the growth of the crop at Wickliffe in 2010 and 2012 differed from the pattern at the other sites. In the very wet spring in 2010 (decile 9.5), the water content of the soil profile actually increased between anthesis and crop maturity in all treatments. The greatest recharge occurred with the half-rate of subsoil manuring. There were no significant differences in water extraction from the subsoil between treatments for the faba bean crop at Wickliffe in 2012 (Table 7).

Yield components and harvest indices for the wheat crops

The yield component that most closely related to increases in estimated wheat yield with the full rate of subsoil manuring was number of ears per m^2. This treatment significantly increased the ear density above that of the control for five of the six wheat crops, the exception being Derrinallum in 2011 (Table 8). The average increase in ear density above these two controls was 60%.

Mixed results occurred for comparisons of ear density between the full rate of subsoil manuring and other non-control treatments (Table 8). At Penshurst in 2009, the full

Table 7. Net losses of water (mm) in the 50–100 cm subsoil layer between anthesis and maturity at the three sites, 2010–12
Differences in soil water were not measured for the mixed fertiliser and subsoil manuring treatment

Treatment	Penshurst			Derrinallum		Wickliffe	
	2010 canola	2011 wheat	2012 canola	2011 wheat	2012 wheat	2010 wheat	2012 faba beans
Control	–2.2	30.3	14.8	27.2	12.0	–9.6	5.2
Deep-ripped	16.6	13.8	29.8	33.2	4.2	–4.1	12.4
Full rate subsoil manuring	40.4	47.1	45.8	18.0	26.7	–8.0	23.4
Half rate subsoil manuring	24.2	33.1	24.4	22.6	4.5	–29.6	33.0
Matched fertiliser nutrients	24.8	14.1	12.4	38.2	2.7	–13.2	12.2
l.s.d. ($P = 0.05$)	24.1	5.6	16.1	–	2.3	5.5	–
P-values	0.026	0.001	0.004	>0.05	0.001	0.003	>0.05

Table 8. Effects of subsoil treatments on the components of wheat yield at the three sites between 2009 and 2012
EN, No. of ears per m^2; GN, no. of grains per ear; GW, grain weight (mg $grain^{-1}$)

Treatment	Penshurst 2009			Penshurst 2011			Derrinallum 2009			Derrinallum 2011			Derrinallum 2012			Wickliffe 2010		
	EN	GN	GW	EN	GN	GW	EN	GN	GW	EN	GN	GW	EN	GN	GW	EN	GN	GW
Control	338	37.1	38.4	305	57.5	38.0	346	42.6	33.9	297	45.4	40.5	286	48.6	45.9	445	48	40.2
Deep-ripped-	361	38.9	32.0	313	60.1	39.0	425	44.4	33.9	275	47.9	38.4	314	48.1	45.8	478	46	41.4
Full rate subsoil manuring	689	38.2	28.9	436	68.0	38.0	581	49.1	34.4	347	48.5	39.6	369	53.1	52.8	627	52	35.9
Half rate subsoil manuring	408	33.9	48.9	398	64.4	39.0	466	47.4	34.9	345	45.7	43.4	354	50.5	49.0	604	50	40.2
Matched fertiliser nutrients	411	35.9	37.9	352	56.4	39.0	452	45.9	34.2	370	47.6	41.9	349	48.6	46.6	520	55	32.5
Mixed fertiliser and subsoil manuring	344	34.2	48.5	332	59.4	34.0	543	46.7	34.7	350	43.3	42	332	53.0	50	576	50	39.7
l.s.d. ($P = 0.05$)	93	–	–	56	–	2.1	103	4.1	–	58	–	–	46	–	–	79	5	3.9
P-values	0.03	>0.05	>0.05	0.001	>0.05	0.002	0.003	0.05	>0.05	0.025	>0.05	>0.05	0.05	>0.05	>0.05	0.002	0.03	0.002

Table 9. Effect of subsoil treatments on harvest indices for wheat crops grown at three sites between 2009 and 2012

Treatment	Penshurst		Derrinallum			Wickliffe
	2009	2011	2009	2011	2012	2010
Control	0.53	0.52	0.42	0.33	0.38	0.49
Deep-ripped	0.46	0.52	0.42	0.34	0.40	0.46
Full rate subsoil manuring	0.56	0.58	0.59	0.40	0.56	0.50
Half rate subsoil manuring	0.56	0.57	0.50	0.34	0.48	0.54
Matched fertiliser nutrients	0.50	0.46	0.50	0.39	0.46	0.47
Mixed fertiliser and subsoil manuring	0.48	0.41	0.53	0.34	0.48	0.50
l.s.d. ($P = 0.05$)	–	0.04	0.08	–	0.07	–
P-values	>0.05	0.003	0.01	>0.05	0.03	>0.05

rate of subsoil manuring resulted in significantly ($P < 0.05$) higher ear density than all other treatments. For another three site-years, the full rate of subsoil manuring generally produced the highest ear density, although not significantly different from one other treatment: the half rate of subsoil manuring at Penshurst in 2011, the mixed treatment at Derrinallum in 2009, and the half rate of manuring at Wickliffe in 2010. There were no significant differences in ear density between the full rate of manuring and the other amendment treatments at Derrinallum in 2011 and 2012.

Number of grains per ear generally did not differ significantly between treatments (Table 8); the exception was at Derrinallum in 2009, where the full rate of subsoil manuring resulted in a significant increase of 5.6 grains ear^{-1} above the control and non-ripped control average of 43.5 grains ear^{-1}. Similarly, the average weight of individual wheat grains did not contribute significantly to the increases in grain yield with the full rate of subsoil manuring. Subsoil treatment did not affect this yield component, except at Penshurst in 2011 and at Wickliffe in 2010; there were significant reductions in grain weights below those of the control for the mixed treatment at Penshurst in 2011, and for the full rate of subsoil manuring and the fertiliser treatments at Wickliffe in 2010 (Table 8).

Harvest indices for wheat crops at all three sites averaged 0.50 across all treatments, except at Derrinallum in 2011, when the average harvest index across treatments was 0.36. Harvest index was significantly ($P < 0.05$) higher with the full rate of subsoil manuring than the control treatments for three of the six wheat crops (Table 9). This difference corresponded to crops where manuring treatments produced yields >4 t ha^{-1} higher than the controls, i.e. Penshurst in 2011 and Derrinallum in 2009 and 2012. The high harvest indices in these three cases averaged

0.58, compared with the average of 0.44 for the respective control treatments (Table 9). For these three wheat crops, the harvest index with the full rate of subsoil manuring was also significantly higher than all other treatments, except for the mixed treatment at Derrinallum in 2009.

Discussion

Grain yield increases with subsoil manuring

Crop responses were to be expected from the addition of nutrient-rich poultry litter to the subsoil, given the deep placement of >600 kg total N ha^{-1} and other nutrients into layers that contained low levels of soil organic matter and total soil N. However, the magnitude, consistency and recurring nature of the estimated yield responses with the full rate of subsoil manuring were somewhat surprising. They occurred at trial sites each time a successful commercial crop was established over the trial plots in the farm paddock. Moreover, they occurred on both a Chromosol and two Sodosols with sodic subsoils. Annual rainfall ranged from a decile 9.3 rainfall of 867 mm at Penshurst in 2010 to a decile 2.5 rainfall at Wickliffe in 2012 with 477 mm (Table 2). All crops in the rotation responded, including wheat, canola and faba beans.

Yield increases were consistent with those occurring for three consecutive crops grown on subsoil-manured land at Ballan, in south-western Victoria, from 2005 to 2007 (Gill *et al*. 2008; Sale *et al*. 2011). Our findings, and those on the Sodosol soil at Ballan, therefore support the first hypothesis that the practice of subsoil manuring can deliver large increases in crop yields across the Victorian high-rainfall zone. The increases in wheat yields of 2–5 t ha^{-1} in this study were in the range of the yield gaps of 2–5 t ha^{-1} predicted by simulations using the APSIM model at four sites in the high-rainfall zone of south-eastern Australia (GRDC 2016). These yield gaps are the predicted differences in yield between soils with subsoil constraints and those without constraints. The continuing nature of the yield responses to subsoil manuring point to a robust soil management intervention that occurred for both the 2005–2007 (Gill *et al*. 2012) and 2009–2012 growing seasons in south-western Victoria. Subsoil manuring appears to have the potential to offer benefits for grain producers in this high-rainfall cropping region of Victoria and more broadly across the south-eastern Australian high-rainfall zone, because of the large areas of land with dense clay subsoils that could respond to subsoil manuring. MacEwan *et al*. (2010) estimated that of the 10.8 Mha of land suitable for cropping across the high-rainfall zone (annual rainfall >500 mm) of south-eastern Australia, ~89% of the soils have clay subsoils with an average bulk density of 1.5–1.6 g cm^{-3}. Although the current costs of implementing subsoil manuring are high, in excess of AU\$1000 ha^{-1}, the consistent yield responses in years with both average and above-average rainfall over 3–4 years mean that subsoil intervention is likely to be profitable (Sale and Malcolm 2015).

The estimated yield increases with the first wheat crops following subsoil manuring at Penshurst and Derrinallum in 2009 and at Wickliffe in 2010 were large, ranging from 2.5 to 4.8 t ha^{-1}. Similarly, there was a large increase in the yield of the first crop at Ballan in 2005 with subsoil manuring. However, consistent increases in the yields of the first crops following subsoil treatment disappeared in 2014 when the canola crop failed to respond to subsoil manuring on a Sodosol at the south-western Victorian site of Westmere (Celestina *et al*. 2018). Rainfall was low in 2014, with less rain falling in spring at Westmere than in spring for the site-years where significant yield responses to subsoil manuring occurred in the first year. For example, the spring rainfall at Westmere in 2014 (74 mm) was considerably less than in the year of the subsoil manuring intervention at Ballan in 2005 (154 mm), at Penshurst (187 mm) and Derrinallum (208 mm) in 2009, and at Wickliffe in 2010 (237 mm). It is therefore possible that low spring rainfall, and perhaps the timing of spring rainfall events, might be responsible for the failure of subsoil manuring to produce responses of crop yields in the first year following the intervention. The impact of seasonal rainfall patterns on the effectiveness of subsoil manuring will be the subject of a companion paper.

An important finding in this study was that the estimated yields with the full rate of subsoil manuring were consistently higher than with the matched N and P fertiliser treatment for eight of the nine site-years in this study. There are several possible explanations for this result. The first is related to the more balanced supply of available N that occurs from the poultry litter than the matched fertiliser treatment. This fertiliser treatment involved placement of 265 kg inorganic N ha^{-1} in a band in the subsoil, with a further 179 kg N ha^{-1} applied as topdressed urea to the first and second crops. By contrast, the full rate of subsoil manuring involved placement of 625 kg total N ha^{-1} in the subsoil band, of which only 31 kg N ha^{-1} was in the NH_4^+ and NO_3^- forms (data not presented). The supply of available N from the mineralisation of organic forms in the poultry litter is likely to continue over time, given the findings of Eghball *et al*. (2002), who reported that the mineralisation of manures can release available N and P nutrients for several years after the manure application. This supply of available N should be adequate for the crop, given that Gill *et al*. (2008) found that tissue-N concentrations in the shoots of the first wheat crop after subsoil manuring were well within the sufficiency range. We argue that the supply of available N from the poultry litter is likely to be closer to the N demand by the crop than the supply from the matched fertiliser treatment. Giller *et al*. (2004) reported that both the profit and the efficiency of N fertiliser use, defined as the crop yield per unit of fertiliser N applied, were maximised when the crop N demand was closely matched to the available N in the soil. The surplus of inorganic N supply over crop demand with the matched fertiliser treatment is therefore likely to reduce N-use efficiency. The N surplus would also predispose the treatment to N fertiliser losses, because denitrification is likely to occur when wet conditions reduce the aeration in the clay subsoils.

A second reason for the superior yields with poultry litter could be the additional macro- and micronutrients present in the poultry litter that were absent with the matched fertiliser treatment. Bolan *et al*. (2010) reported concentrations of additional macronutrients in poultry litter to be in the order of 16.2 g calcium, 3.5 g magnesium and 5.2 g sulfur kg^{-1}, with micronutrient concentrations as high as 300 mg copper, 250 mg manganese, 327 mg zinc and 5 mg molybdenum kg^{-1}.

A third possibility is that the higher yields with poultry litter resulted from improved root growth in the subsoil. Gill *et al*. (2008) reported that increased root growth and higher crop yields were both highly correlated with improved physical properties in the clay subsoil at Ballan, compared with the control plots. The Ballan results occurred during the first wheat crop grown on subsoil-manured plots in 2005. If subsoil manuring in this 2009–12 study increased deep root growth in the subsoil, then this may correspond to the observed greater depletion of subsoil water by the crop. The full rate of subsoil manuring resulted in significantly greater water extraction from the 50–100 cm subsoil layer at four of the seven site-years relative to the control (Table 7). Similar results occurred at Ballan in 2005 where large increases in wheat yields from subsoil-manuring plots were associated with increased extraction of subsoil water (Gill *et al*. 2008, 2009).

We argue that an important contributing factor to the yield response to subsoil manuring was the increased deep root growth and associated microbial activity in the subsoil. Such outcomes would, in turn, improve aggregation of the clay, with increases in the porosity and permeability of the subsoil. Numerous studies (Tisdall and Oades 1979; Reid and Goss 1981; De Gryze *et al*. 2005; Clark *et al*. 2009) and reviews (Degens 1997; Six *et al*. 2004; Bronick and Lal 2005) support the direct link between biological activity in a soil and improvement in its soil structure. However, additional experimental data are required to support this view.

Under the conditions of these field experiments, it is unlikely that N supply was the driver of yield responses for the wheat crops at Penshurst in 2009, and at Derrinallum in 2009 and 2012. The wheat plants with matched nutrients were all high in N, as indicated by their grain protein concentrations exceeding 11.6% (Tables 4 and 5), yet their estimated grain yields were significantly less than yields with deep-banded poultry litter. Holford *et al*. (1992) reported that grain protein concentrations in excess of 11.6% indicate that wheat plants are adequately supplied with N, and would be unlikely to respond to additional N. Although N supply may not have been the key driver for the grain yield responses to subsoil manuring for these site-years, it is still likely that N in the organic amendment would have played a key role in stimulating deep root growth of wheat and canola plants and the extraction of deep subsoil water. Numerous researchers have reported how high N supply increases water extraction from deeper layers in the root-zone (Fischer and Kohn 1966; Norton and Wachsmann 2006; Sadras *et al*. 2012).

A crucial issue with subsoil manuring is the longevity of the benefit. The large increase in estimated yield response in 2012 of 2 t ha^{-1} for canola at Penshurst and 4.1 t ha^{-1} for wheat at Derrinallum from the full rate of subsoil manuring occurred with the fourth consecutive crop at both sites after the manuring intervention in 2009. Whether large responses will continue for subsequent crops is unclear but will potentially depend on two processes. The first is the depletion of nutrients from the amendment, due to nutrient removal in high-yielding crops. Using the nutrient-removal calculator developed by the International Plant Nutrition Institute (IPNI 2016), we determined that over the four crops at Penshurst, the extra grain removed ~48% of the N and 16% of the P added in the initial poultry-litter application. Nitrogen depletion therefore is likely to become an issue, particularly if there are losses of N from nitrate leaching and denitrification. The second process that would diminish yield responses would be a deterioration in the physical structure of the clay subsoil, assuming that improvements in the physical structure of the subsoil had occurred with subsoil manuring. We observed that enhanced aggregation across the clay subsoil lasted 4 years following subsoil manuring at Ballan in 2005 (Sale *et al*. 2011). In order to prolong the yield benefits in such soil, it will be necessary to manage fertiliser nutrients in the longer term so that nutrient supply matches any increased supply of subsoil water that might develop with subsoil manuring.

Yield components that contributed to crop responses to subsoil manuring

The increased density of fertile tillers, resulting in greater numbers of ears per m^2, consistently contributed to the increases in estimated wheat yield with the full rate of subsoil manuring. This yield component was significantly higher in the subsoil-manured crops than the control crops for five of six wheat crops in the study (Table 8). Several factors are likely to have contributed to this higher ear density in subsoil-manured crops. First, an increase in the supply of subsoil water and nutrients with subsoil manuring would reduce the intense competition among tillers for limited assimilate during the stem-elongation and ear-development phase (Miralles and Slafer 1999). Assimilate supply from photosynthesis would likely be more limited in the control treatment during this critical growth period, owing to the more restricted supply of water and/or nutrients in the control. Thus, more tillers would have survived to produce ears in the subsoil-manured treatment. The second factor is the higher N status in the subsoil-manured plants. This occurred in the 2005 Ballan study (Gill *et al*. 2008) and it is likely to have occurred in this study, given the high protein concentrations in the wheat grain. High N status leads to increased rates of tiller initiation during the tillering phase (Spiertz and De Vos 1983; Salvagiotti and Miralles 2007). Finally, the possibility of improved aeration in the treated subsoils would reduce any transient or severe waterlogging stress during the wet winter months, and so avoid reductions in tiller numbers. Several studies (Belford *et al*. 1985; Collaku and Harrison 2002; Condon and Giunta 2003) have shown how periods of waterlogging during vegetative growth reduce tillering in wheat.

There was one site-year in this study when a significant increase in the grain number per ear also contributed to the response of the wheat crop to subsoil manuring. This was at Derrinallum in 2009, when subsoil manuring produced the largest increase in estimated yield of 4.8 t ha^{-1} above the yield of the control crop. The wheat plants in this treatment were able to produce 15% more grain in each ear than control plants. The nutrient release from the mineralising poultry litter during the early spring period, in a subsoil that was low in total organic carbon and total N compared with the Penshurst subsoil (Table 1), and the favourable spring rainfall (Table 2) meant that these subsoil-manured plants were well supplied with soil resources (water and nutrients) compared with the control plots. It is further likely that these resources were sufficient to increase the survival of young tillers and the survival rate of developing floret primordia during the final few weeks before anthesis. This is the stage of development when the most intense competition for resources occurs between expanding leaves and tillers, and developing spikelets and florets (Fischer 1985; Savin and Slafer 1991). The outstanding result highlights the high yield potential of subsoil-manured crops under conditions that prevailed at Derrinallum in 2009.

A further benefit from the likely enhanced supply of soil resources for the subsoil-manured wheat crops was the higher harvest index for some site-years. This occurred with wheat crops that produced large increases in estimated yield, in excess of 4 t ha^{-1}, with the full rate of subsoil manuring. These were the crops at Derrinallum in 2009 and 2012, and at Penshurst in 2011. These crops had significantly higher harvest indices of 0.56–0.59 compared with the control plants with an average index of 0.44. Gill *et al*. (2008) described how the subsoil-manured crops at Ballan in 2005 had very high harvest indices >0.60. The authors attributed the high harvest index values in part to the delay in the senescence of the flag leaf, which enabled assimilate to continue to move to the filling grains during the late grain-filling period. It is likely that this also occurred when there were large yield responses in subsoil-manured crops in this study.

Conclusions

Subsoil manuring resulted in consistent increases in estimated grain yields at three sites in the high-rainfall zone in south-western Victoria between 2009 and 2012, in years when rainfall was generally average or above average. In these years, it is likely that subsoil manuring increased the supply of nutrients and improved crop access to soil water in the subsoil. In wet years, we suspect that improved aeration in the subsoil, together with the increased supply of nutrients, contributed to the yield increases.

Conflicts of interest

The authors declare no conflicts of interest.

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