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Agronomic consequences of tractor wheel compaction on a clay soil

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Abstract

In southern New South Wales, Australia, farming operations using tractors often occur when the soils are moist and prone to soil compaction. However, the extent of soil compaction and its relative impact on crop yield have not been quantified in the region. In this experiment, re-compaction due to tractor wheel traffic in a sodic brown clay (Vertisol) was monitored under simulated controlled traffic conditions after removal of a pre-existing subsoil pan by deep tillage. Soil physical properties under wheel tracks were compared to those between wheel tracks in terms of bulk density, penetrometer resistance, water content, air-filled porosities and changes in ‘‘least limiting water range’’. Differences in the growth and yield of canola (*Brassica napus*) and wheat (*Triticum aestivum*) in the two areas were also measured. Although deep ripping increased canola yield by 20% (from 2.0 to 2.4 t ha^{-1}), reformation of a compaction pan under the wheel tracks was already detected in the first season of cropping. In the second cropping year, soil in the 0.05–0.10 m layer under wheel tracks had significantly higher penetrometer resistance (>2000 kPa) and bulk density (1.5–1.58 Mg m^{-3}) and lower air-filled porosity (0.07–0.09 m^3 m^{-3}) compared to that measured between wheel tracks (<1000 kPa and 1.25–1.29 Mg m^{-3}, and 0.187–0.226 m^3 m^{-3}, respectively). The ‘least limiting water range’ was essentially reduced to zero under wheel tracks and hence was unfavourable to plant roots. By contrast, favourable conditions were maintained in the area between wheel tracks throughout the whole available water range. This finding was supported by a significant reduction in canola and wheat root growth in the layer under the wheel tracks. While there was no difference in wheat yield (5.3–5.5 t ha^{-1}), canola grain yield on the wheel track was only 34% of that between wheel tracks (1.1 t ha^{-1} versus 3.2 t ha^{-1}). The canola results highlight the potential loss in grain yield due to compaction by tractor wheel traffic and indicate the likely benefits of adopting controlled traffic in farming systems for the sodic brown clay soils of this region. However, to fully realise the benefits of controlled traffic on these soil types it may first be necessary to remove the

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underlying compaction generated by previous farming practices. Conversely, adoption of controlled traffic systems should greatly assist in slowing the rate of recompaction of cropping soils following deep ripping.

Keywords: Least limiting water range; Controlled traffic; Deep ripping; Sodic soils

1. Introduction

Soil compaction by machinery traffic in agriculture is a well recognised problem in many parts of the world (e.g. Raghavan et al., 1990; Soane and van Ouwerkerk, 1994; Hamza and Anderson, 2005). The extent of the soil compaction problem is a function of soil type and water content, vehicle weight, speed, ground contact pressure and number of passes, and their interactions with cropping frequency and farming practices (Larson et al., 1994; Chamen et al., 2003). Compaction induced by vehicle traffic has adverse effects on a number of key soil properties such as bulk density, mechanical impedance, porosity and hydraulic conductivity (Radford et al., 2000; Hamza and Anderson, 2005). All of these factors can potentially reduce root penetration, water extraction and plant growth (Kirkegaard et al., 1992; Passioura, 2002), and evidence of reductions in crop yield as a result of soil compaction have been reported for both dryland (rainfed) cropping systems (e.g. Ellington, 1986; Radford et al., 2001; Hamza and Anderson, 2003; Sadras et al., 2005) and irrigated crops (e.g. McGarry and Chan, 1984; McGarry, 1990; Braunack et al., 1995) across a wide range of soil types and environments. From a management point of view, it is useful to identify the processes responsible for changes in soil physical properties so that farming systems and practices can be adopted to either ameliorate, avoid or minimise soil compaction problems and reduce the subsequent risk of poor agronomic performance.

The cropping belt of southern New South Wales (NSW), Australia, produces 20% of the total Australian grain crop and represents around 40–45% of the grain grown in south-eastern Australia (Knopke et al., 2000). The soils of the region in the lower part of the landscape are commonly heavy clays (Vertisols, also classified as Vertosols using Australian soils nomenclature; Isbell, 2002) and red brown earths (Alfisols, classified as Red Chromosols using Australian soils nomenclature; Isbell, 2002) with poor internal drainage. Tillage and sowing operations on these soils are often carried out after autumn rain when the soil is moist and vulnerable to compaction. The extent of soil compaction in southern NSW due to wheel traffic and its agronomic consequences have not been investigated (McGarry, 1996); however, it is believed to be very widespread (Hamblin, 1991; Chan et al., 2003). Serious crop losses on Vertisols and Alfisols due to waterlogging are common in wet seasons (McCallum et al., 2001); particularly for canola (*Brassica napus*) and legume crops which tend to be more sensitive to waterlogging than cereals such as wheat (*Triticum aestivum*) (Gregory, 1998). The extent to which waterlogging induced reductions in crop production has been exacerbated by soil compaction due to wheel traffic is not certain.

A common approach taken by many farmers cropping on Vertisols in southern NSW who suspect they may have potential problems with soil compaction has been deep tillage (ripping) to disrupt subsurface pans. Such deep ripping treatments are expected to facilitate enhanced root growth and crop yield (see Kirkegaard et al., 1992; Hamza and Anderson, 2005) and growers claim to observe subsequent improvements in crop performance; however, many farmers also report that the benefits often do not appear to persist beyond 1–2 years. Perhaps this should not be too surprising given that more than 60% of the ground area is likely to be trafficked by the tyres of heavy machinery annually using minimum tillage systems and 80–90% of the land area might experience wheel traffic at least once a year with conventional farming practices (Soane and van Ouwerkerk, 1994; Radford et al., 2000). Therefore, the reformation of compaction layers would seem to be inevitable.

One approach that has been proposed to minimise machinery-induced compaction is to utilise controlled traffic systems whereby vehicle traffic and the resulting soil compaction is restricted to either permanent wheel tracks or sacrificial lanes across a field (Reeder, 2002; Hamza and Anderson, 2005). This leaves the cropped area either free of all traffic, or limits the impact of vehicle movement to certain periods in the production cycle (Chamen et al., 2003). With a controlled traffic system the wheel track lanes, which can represent 15–20% of the total land area (Tullberg, 2000) become progressively more compacted. However, at the same time, there can be marked improvements in soil structure and water infiltration rate in the land area between the lanes which is no longer regularly driven over (Campbell et al., 1986; Li et al., 2000). In other words, the separation of traffic lanes from cropping zones using controlled traffic can potentially maintain optimal conditions for both wheel traction and crop growth (Taylor, 1983). Indeed, many of the advantages of controlled traffic are derived specifically from providing a firm base for tractor and combine tires which allows earlier sowing opportunities and more timely farm operations and harvest (Reeder, 2002). Other benefits may be reflected in savings of fuel costs, eliminating waste from overlaps, or reducing yield reductions due to gaps in application of fertilizers or agrichemicals (Hamza and Anderson, 2005). However, to fully realise the benefits of controlled traffic existing equipment and implements may need to be modified to align wheel spacings and/or new machinery to be purchased that employs automatic guidance control to provide the precision in vehicle movement that is needed to ensure that exactly the same tracks are traversed by every farming operation year after year (Reeder, 2002).

While controlled traffic has been demonstrated to increase root and crop growth under a range of environments (Hamza and Anderson, 2005), yield improvements are not always observed. Such situations can arise when the underlying impediments to root growth have not been removed prior to imposing controlled traffic and the soil is slow to self repair, or they might reflect growing seasons where an adequate water supply results in either a reduced level of soil strength during crop development and/or a limited crop reliance on subsoil water for growth (Kirkegaard et al., 1992; Braunack et al., 1995; Radford et al., 2000).

In the study reported here, we monitored the formation of a subsoil compaction pan due to wheel traffic following deep ripping of a clay soil. The physical properties of the compacted soils were characterised and related to the growth and yield of wheat and canola, the two most commonly grown crops in the region. The trial also provided an opportunity to assess the potential crop and soil benefits from using controlled traffic systems in southern NSW to provide the necessary local data that will allow farmers and their advisors to evaluate the economic viability of adopting such systems based on crop response and value.

2. Materials and methods

2.1. Experimental site and soil

The on-farm investigation site was located at Grogan, NSW, Australia (34.31°S, 147.81°E). The soil was a sodic brown clay (Vertisol). Clay content was 320 g kg^{-1} at 0.1 m increasing to 600 g kg^{-1} at 1.5 m depth. The soil was sodic at the surface (exchangeable sodium percentage (ESP) = 12% at 0–0.10 m) and sodicity increased down the profile to >25% beyond 0.50 m depth. Electrical conductivity of saturation extract (EC_e) was >4 dS m^{-1} at 0.40 m depth. The site had been cropped for many years in rotation with periods of pasture of 3–5 years. Preliminary soil data had indicated the presence of a compacted zone at 0.10–0.20 m depth. Average annual rainfall at the trial site was 535 mm with a fairly even distribution throughout the year (Table 1). Total annual rainfall during the experimental period was 586 mm in 2000 and 431 mm in 2001, with 353 and 308 mm, respectively, occurring during the main April–October crop growing season (compared with 321 mm average, Table 1). The higher than average rainfall in 2000 (particularly the 103 mm in March, 85 mm in August and 87 mm in November) contributed to local waterlogging and crop losses, but not in the treatments described here where gypsum had been applied to ameliorate topsoil sodicity and improve water infiltration (Jayawardane and Chan, 1994; Hamza and Anderson, 2003).

2.2. The field experiment

The on-farm site was sown to lucerne (alfalfa, *Medicago sativa*) in May 1999 to dry out the profile to

Table 1
Comparison of monthly rainfall during experimentation with the long-term average at the Grogan on-farm trial site in southern NSW

Month	Rainfall (mm)		
	2000	2001	Long-term average[a]
January	14	10	49
February	22	40	37
March	103	33	42
April	33	44	44
May	52	21	46
June	54	71	42
July	43	37	47
August	85	28	46
September	31	45	42
October	55	62	54
November	87	34	46
December	7	6	41
Total annual	586	431	535

[a] Australian Bureau of Meteorology.

facilitate the removal of the pre-existing pan by ripping prior to experimentation. Gypsum was applied across the site at a rate of 5 t ha^{-1} prior to sowing. Glyphosate was applied at 1526 g ha^{-1} on 5 November 1999 in 100 L ha^{-1} water to kill all grass and broadleaf weeds and again on 2 February 2000 at 540 g ha^{-1} in a mixture with 2,4-D amine present as *iso*-propylamine salt at 675 g ha^{-1} at a water rate of 100 L ha^{-1} to remove the lucerne. The site was deep tilled to a depth of 0.15 m on 14 January 2000 at 0.35 m spacings using an Agroplow[R] and again deep tilled on 9 February to a depth of 0.20–0.25 m to remove the compacted layer. It was then scarified to 0.10 m and harrowed on 29 February to reduce the clod size. The site was sprayed with 2,4-D present as *iso*-propylamine salt at 675 g ha^{-1} with glyphosate at 360 g ha^{-1} using 100 L ha^{-1} water on the 31 March 2000 to remove residual lucerne plants that survived the earlier herbicide treatment. Gypsum was applied at a rate of 2.5 t ha^{-1} on the 11 April and scarified to a depth of 0.10 m.

2.2.1. Cropping details 2000

The site was sown on 19 April to a range of pasture and crop species on plots arranged in a completely randomised block design. This included two replicates for each of canola and wheat. Wheat, cv. Rosella (80 kg ha^{-1}) and canola, cv. Oscar, (5 kg ha^{-1}) were sown on April 19 with 20 kg P ha^{-1} and 25 kg S ha^{-1}, and all plots were sprayed with bifenthrin at 30 g ha^{-1} for earthmite control. Plot size was 4.5 m × 24 m (comprised of 20 rows) with the width equivalent to two tractor passes. The tractor used for sowing was a Ford 4130 (41 kW). Tractor weight was 2938 kg. Rear tyres were 0.35 m wide, pressure = 160 kPa; front tyres were 0.19 m wide, pressure = 230 kPa.

All tractor traffic was restricted to the same path so that the wheel track and non-wheel track areas on the plot were maintained during the course of this investigation. Four replicates of canola (4.5 m × 24 m) were also sown in an adjacent un-ripped area which had received gypsum treatment. Wheat and canola was subsequently sprayed with herbicides to control grass and broadleaf weeds following standard commercial practice. Both crops were topdressed with urea (48 kg N ha^{-1}) on 18 July and wheat received a further 60 kg N ha^{-1} on 13 September.

2.2.2. Cropping details 2001

The four continuous crop plots were scarified and harrowed once to a depth of between 70 and 80 mm on the 30 April. Wheat, cv. Diamondbird (80 kg ha^{-1}) and canola, cv. Hyola 60 (5 kg ha^{-1}) were sown using a cone seeder on the 9 May at a depth of 50–60 mm for the wheat and 10–30 mm for the canola with 20 kg P ha^{-1} and 25 kg S ha^{-1} and 60 kg N ha^{-1} as urea. Canola was sown in the deep-ripped experimental plots where wheat had been grown in 2000 and wheat was sown were canola had previously been. The neighbouring un-ripped plots were sown to faba bean (*Vicia faba*), so no direct with and without deep ripping comparison of crop growth and yield was possible in 2001. Weeds were controlled in all plots using standard commercial practice, and canola sprayed with mancozeb to protect the seedlings against attack by downy mildew. Nitrogen was topdressed onto the cropping plots at a rate of 53 kg N ha^{-1} as ammonium nitrate on the 17 August.

2.3. Soil physical measurements

In the first experimental year (2000), penetration resistance of the soil under the wheel tracks, between the wheel tracks, as well as on an adjacent un-ripped area, was measured after sowing of the crops using a penetrometer (Rimik[R]) made to comply with ASAE standard and has a cone angle of 30° and base diameter of 12 mm. In the second cropping year (2001), when the soil was close to field capacity, penetration resistance along a transect across the plot on alternate rows and down the profile to 0.45 m was measured using a penetrometer (i.e. 10 insertions per plot over 4.5 m width). Two transects were randomly selected on each plot. Measurements were carried out on all the wheat and canola plots. In 2001, changes in penetration resistance of the 0.05–0.10 m layer as a function of soil water content were monitored in a drying cycle beneath the wheel track (row 10) and non-wheel track (row 15) areas. For each area on each measurement occasion, three penetrometer insertions were carried out and one soil sample at 0.05–0.10 m was collected for gravimetric water content determination. At one sampling (83 days after sowing), bulk density of the 0.05–0.10 and 0.10–0.20 m layer at each sampling point was measured using the core method (Chan, 1981), while air-filled porosity was determined as described by Hodgson and MacLeod (1989).

2.4. Crop measurements

Plant populations were determined in May 2000 and June 2001, 2–3 weeks after emergence using two approaches that involved counting the number of plants in: (a) ten 1 m rows per plot and (b) from three 0.54 m^2 quadrants per plot. Grain yield was determined for canola (on 24 November 2000 and 11 November in 2001) and wheat (on 5 December 2000 and 21 November in 2001) by machine harvesting two strips 1.55 m wide by 22.5 m long from each plot using a small plot header.

In 2001, root density of the soil in the wheel track and non-wheel track positions was measured using soil samples collected 83 days after sowing. Roots in pre-weighed sub-samples of soil from three replicated cores collected from each crop row 10 (under wheel track) and 15 (between wheel tracks) at 0.05–0.10 m (Fig. 2) as well as from loose samples (0.10–0.20 m) were recovered following washing with 0.3% Calgon and their dry weight measured after drying at 70 °C.

Crop biomass and grain yield were measured in the presence and absence of wheel traffic on November 8 (canola) and 11 (wheat) in 2001 by cutting all above-ground crop biomass from three replicates in each plot of 0.8 m lengths of crop rows growing on the wheel track (combined rows 9–11) and between the wheel tracks (combined rows 14–16). Each replicate represented the equivalent of 0.54 m^2 (i.e. a total of 1.62 m^2 harvested from crop rows for both under a tractor wheel track and between the wheel tracks in each plot). The number of plants in each 0.8 m of cut row was determined and the harvested vegetative material was separated from the grain for each of the three replicates in each canola and wheat plot and was weighed after 2 days at 70 °C.

3. Results and discussion

3.1. Reformation of a compaction zone following deep ripping

Comparing the penetration resistance profiles from the un-ripped area with the non-wheel track ripped plots showed that the pre-existing compaction layer had been successfully removed by deep tillage (Fig. 1). Penetrometer data collected directly under the wheel tracks after sowing in 2000 indicated that a compacted zone was already re-forming in the 0–0.10 m layer in the first year of cropping (Fig. 1). Further evidence of soil compaction as the result of wheel traffic became apparent from penetrometer

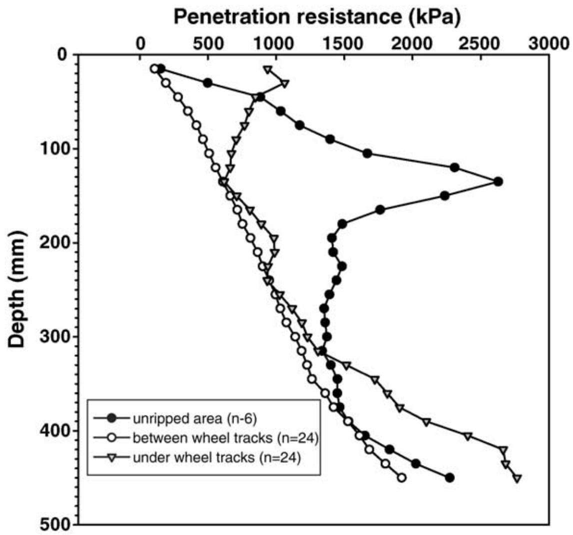

Fig. 1. Change in penetration resistance down the soil profile in unripped soil, and beneath and between wheel tracks in areas subjected to deep (0.20–0.25 m) tillage measured after sowing in 2000.

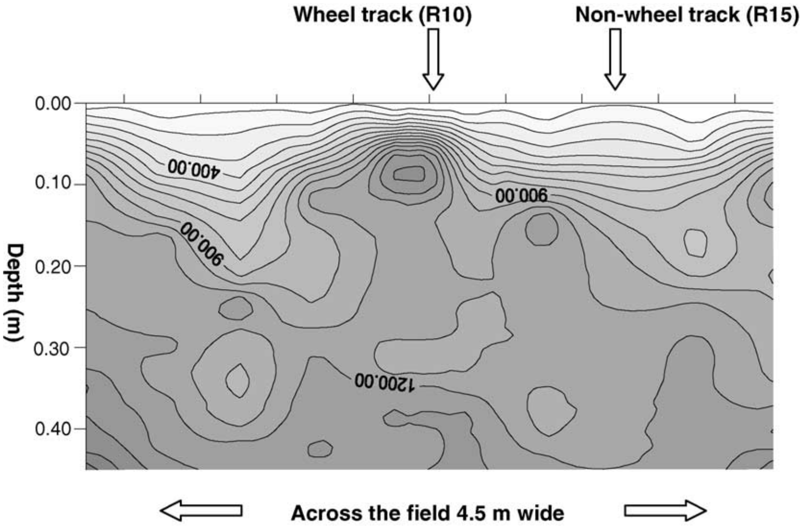

Fig. 2. Contour plot showing distribution of penetration resistance (kPa) of soil profile cross section perpendicular to direction of tractor traffic. R10 and R15 indicate the location of key crop and soil measurements collected in the presence (row 10) and absence (row 15) of wheel traffic.

measurements undertaken after sowing the second crop since deep ripping in 2001 (Fig. 2). The contour plot presented in Fig. 2 represents the distribution of penetration resistance across the field plots and down the soil profile and clearly indicated the reformation of a compacted layer at 0.05–0.10 m on rows 1, 10 as well as 20 corresponding to the location of the wheel tracks. The higher soil strength found under the wheel track was also supported by differences in bulk density found in the presence and absence of wheel traffic under both canola and wheat crops in 2001 (Table 2). The mean bulk density in 0.05–0.10 m layer for the crops was 1.54 Mg m^{-3} versus 1.27 Mg m^{-3}, respectively, for the wheel track and non-wheel track areas. A bulk density of 1.54 Mg m^{-3} falls within the range of limiting values for root growth for clay soils (Jones, 1983).

The data in Fig. 3 represent the changes in penetration resistance as a function of soil water content for soil in the 0.05–0.10 m layer both under the wheel track and in non-wheel track areas. For the soil under the wheel track, penetrometer resistance was higher than that between the wheel tracks throughout the whole soil water content range under

Table 2
Soil physical conditions, root mass density, crop biomass, grain yield and harvest index determinations for canola and wheat growing in the wheel track and in non-wheel track areas in 2001 (numbers within brackets refer to standard errors)

Parameter	Canola		Wheat	
	Wheel	Non-wheel	Wheel	Non-wheel
Bulk density (Mg m^{-3})[a]	1.58*[d] (0.01)	1.29 (0.04)	1.50* (0.01)	1.25 (0.02)
Air-filled porosity at FC (m^3 m^{-3})[b]	0.07* (0.01)	0.19 (0.02)	0.09* (0.01)	0.23 (0.01)
Root mass density ($\times 10^{-3}$ g per m^3 soil)	9.2* (1.5)	27.5 (12.7)	75* (19)	118 (21)
Crop biomass (t dry matter ha^{-1})	4.7* (0.6)	11.8 (1.6)	12.0 (0.5)	12.6 (0.8)
Grain yield (t ha^{-1})	1.1* (0.2)	3.2 (0.4)	5.5 (0.4)	5.3 (0.2)
Harvest Index (%)[c]	22*	27	43	44

[a] 0.05–0.10 m soil layer.
[b] FC = field capacity in the 0.05–0.10 m soil layer.
[c] Harvest index (%) = 100 × (grain yield)/(crop biomass).
[d] Values under wheel tracks followed by (*) are significantly different ($P < 0.05$) from the corresponding values under non-wheel tracks for the same crop.

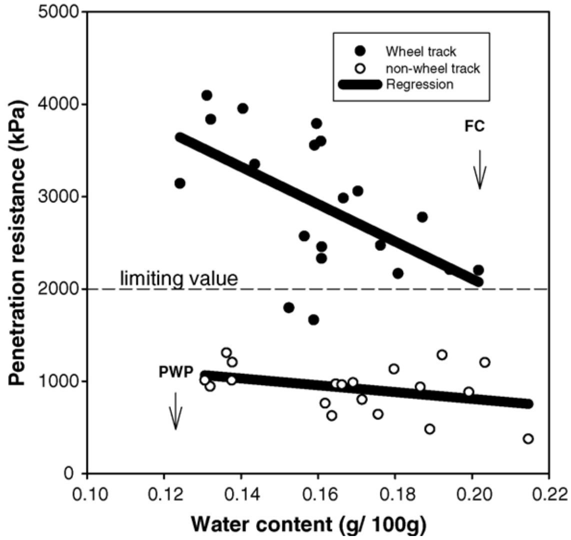

Fig. 3. Changes in penetration resistance as function of soil water content at 0.075 m depth under wheel track as well as between wheel track (FC = field capacity; PWP = permanent wilting point, each data point represents mean of three measurements) measured in 2001.

investigation. Furthermore, while penetration resistance of the soil beneath the wheel track increased markedly as soil water content decreased (i.e. became drier), it remained relatively unchanged in the absence of tractor wheel traffic. As a result, the difference in penetration resistance increased as the soil dried (Fig. 3). Throughout the available water range, penetrometer resistance of the soil under the wheel track was above 2000 kPa, a level of soil hardness commonly used to indicate a critical threshold for root growth (Da Silva and Kay, 1997; Hamza and Anderson, 2005). The higher soil strength of the pan was supported by significantly higher bulk density of the soil layer under the wheel track compared to that between the wheel tracks area. Even at 'field capacity', air-filled porosity was only 0.07 $m^3\ m^{-3}$ (Table 2). This measure was lower than the 0.1 value which is often quoted as the critical lower limit for adequate soil aeration (Grable and Siemer, 1968). Therefore, this zone of soil under the wheel track had conditions potentially limiting for root growth through the available water range and accordingly the least limiting water range (LLWR) (Letey, 1985; Da Silva and Kay, 1997) was virtually zero. In contrast, the same location within the soil profile between the wheel tracks had more favourable soil physical conditions in terms of aeration and soil strength throughout the whole available water range. Penetration resistance was far below the critical value of 2000 kPa even at permanent wilting point in the case of between the wheel track areas.

3.2. Crop response

Despite the differences in total annual and crop growing season (April–October) rainfall in 2000 and 2001 (Table 1), similar grain yields were achieved for wheat and canola in both years (Table 3). Crop performance in the presence and absence of deep ripping could only be directly compared in 2000, but the data indicated a statistically significant 20% improvement in canola yield (from 2.0 to 2.4 t ha^{-1}; $P < 0.05$) in response to the removal of the subsurface compaction pan (Table 3), even though both canola crops had the same plant populations (53–54 m^{-2}). The level of yield increase observed in the first canola crop after deep ripping is similar to

Table 3
Grain yield from header harvest of wheat and canola sown at the Grogan trial site in 2000 and 2001 (numbers within brackets refer to standard errors)

Treatment and crop	2000		2001	
	No. replicates	Grain yield (t ha^{-1})	No. replicates	Grain yield (t ha^{-1})
Deep ripping + gypsum				
Wheat	2	5.1 (0.05)	2	5.2 (0.08)
Canola	2	2.4[a] (0.03)	2	2.1 (0.19)
Unripped + gypsum				
Canola	4	2.0[a] (0.06)	–	na[b]

[a] Yield of deep ripped canola was significantly greater than the unripped canola ($P < 0.05$).
[b] na indicates that since faba bean was sown in the unripped gypsum plots in 2001 comparative yield data were not available.

improvements reported for other dryland crops elsewhere in Australia in the first year or two after ripping treatment (Ellington, 1986, up to 50% yield improvement, 17% average; Radford et al., 2001, up to 55%, 19% average; Hamza and Anderson, 2003, up to 30%, 17% average; Sadras et al., 2005, up to 43%, 20% average).

For the canola crop in 2001, root mass density at 0.05–0.10 m depth measured under the wheel track 85 days after sowing was only 33.5% that found in the absence of wheel traffic (Table 2). For the wheat crop, while greater root mass density was found at both locations than the canola crop, root mass density found under the wheel track was 65% of that found under the non-wheel track area. Therefore, for both crops, root mass density found in the 0.05–0.10 m layer under the wheel tracks was significantly lower than that found between wheel tracks (Table 2). A similar difference was also observed in the 0.1–0.2 m layer (results not shown). Both shoot dry matter production, grain yield and harvest index of canola were significantly lower on the wheel track rows (WT) compared to those between the wheel track rows (NWT). This is despite there being no statistically significant difference in the canola plant populations (57 m^{-2} in WT versus 63 m^{-2} in NWT). Canola yield under the wheel tracks was only 34% of that between wheel tracks. However, no such differences were detected in the case of wheat (Table 2). This apparent lack of response by wheat to compacted soil is by no means unique (e.g. Radford et al., 2000). The relative impact of wheel traffic on above-ground growth and grain yield by canola and wheat (Table 2) could reflect differences in the sensitivities of the tap root system of canola and the fibrous root systems of wheat to soil compaction and the associated differences in soil physical properties. Moreover, the compacted soil also created a poorer aeration status under wet conditions which would make it less favourable for crops such as canola which tends to be more sensitive to waterlogged conditions than wheat (Gregory, 1998).

4. Conclusions

Results highlighted the vulnerability of the Vertisol to wheel track compaction and the associated potential yield losses for sensitive crops such as canola. This is expected to be a common occurrence under conventional farming systems involving random uncontrolled traffic. Alternative systems such as controlled traffic may need to be adopted for the more sustainable management of these soils in the region. However, to fully realise the production benefits of controlled traffic for crops such as canola on these soil types it may first be necessary to remove the underlying compaction generated by previous farming practices with deep ripping. One of the other implications of imposing controlled traffic systems on deep ripped soils is that controlled traffic could also assist in retaining longer term benefits of deep ripping to ameliorate sub-surface compaction pans.

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