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The soil structural cost of traffic from heavy machinery in Vertisols

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ABSTRACT

The agricultural industry has a strong and continuing trend for the incorporation of heavy machinery into the farming system, in order to create operational efficiencies. It is therefore important to understand the soil structural cost of such machinery, which was the objective of this work. Using the John Deere 7760 (JD7760) cotton picker (soil surface stress at the rear wheel ≈0.5 MPa), as a case study, seven randomly allocated experimental sites within the Australian cotton industry were investigated for changes in soil bulk density after traffic with the JD7760. The modified Proctor test optimum moisture content (OMC) for compaction was measured, based upon the JD7760 imposed surface stress, and compared to the field results for compaction. Soil water deficits, calculated for the modified Proctor test OMC, were determined and used to discuss the soil structural implications of heavy machinery, as well as threshold soil water content for safe traffic. All sites underwent significant soil compaction within the 0.3 m depth. More than 50% of sites exhibited compaction to the limit of investigation (0.8 m depth), with the remaining sites having significant reduction in spatial heterogeneity of Vertisol cracks and macropores for the same depth. General equations for OMC and plastic limit, based on clay content and OMC, respectively, were developed. These were used to facilitate extrapolation of experimental data to an open-database of 116 Vertisol sites. For these data, it was determined that safe traffic thresholds did not exist above to the lower limit (soil matric potential −1.5 MPa). Implications for soil structural relations and soil-water movement are discussed.

1. Introduction

There has been a recent and clear trend toward the use and development of larger and more powerful agricultural machinery to increase the effective capacity, or in field efficiency. This trend will likely continue (Kutzbach, 2000; Bennett et al., 2015; Antille et al., 2016) at the risk of significant soil compaction, particularly in the subsoil. Such a trend means increased axle loads, in most cases, leading to continued increase in subsoil stresses (Keller and Arvidsson, 2004), with numerous studies (e.g., Chamen, 2015) suggesting stresses can be as great as 0.3 MPa at 0.4 m soil depth (e.g., from combine harvesters with an overall load ≥30 t).The effects of subsoil compaction are not easily remediated, resulting in often persistent impact, unless energy demanding tillage is undertaken. However, the result of such tillage is variable and potentially short-lived, due to subsequent traffic (Logsdon et al., 1992; Alakukku, 1999; Tullberg, 2000; Chamen, 2015). Consequently, the tendency towards adoption of more efficient machines to reduce costs and increase work rates has brought about concern, due to the potentially negative effects of increased soil compaction and the associated need for tillage repair.

Increased machinery size has the drawback of increased axle loads, and subsoil stresses (Keller and Arvidsson, 2004). In grain cropping, Chamen (2015) estimated an average 14-fold increase in subsoil stresses (from about 0.02–0.28 MPa at 0.4 m depth) between 1930 (horse-ploughing) and 2010 (30 Mg combine harvesters), respectively. What constitutes 'heavy machinery' should not simply be a function of the machine mass, but determined by mass at the wheel, the associated stress state distribution, and the characteristics of the soil that it will traffic. Håkansson (1990) states that the maximum load at the soil interface should be much less than 0.2 MPa. Whilst this has well been exceeded in modern agriculture, such a limit would minimise compaction of Vertisols—the major soil type in Australian cotton production (McKenzie, 2001) — due to overcoming the average precompression stress (≈0.1 MPa, and a volumetric soil moisture ratio average of 0.319, $n = 170$) with depth (Kirby 1990). Therefore, we define 'heavy machinery' as that applying stress > 200 kPa at the soil surface.

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Cotton harvesting technology has undergone significant operational improvement, whereby the requirement for multiple operations such as harvesting, chaser bins (boll buggies) and module building (compression of cotton for transport to processing plant) has been decreased to a single machine operation (see Bennett et al., 2015). Both Case IH (the Module Express 625) and John Deere (the model 7760) have produced these cotton harvesters with increased wheel load and a six-row harvest frontage. Thus, resulting in no change to the number of required machine passes, but significantly increasing the load the soil must endure at each pass. Within Australia the John Deere 7760 (JD7760) has undergone rapid adoption from inception in 2008 to ≈80% adoption by 2013 (Bennett et al., 2015). For Australia, the Case IH Module Express 625 (CIH625) has not been adopted at all, but is highly utilised within American cotton systems alongside the JD7760 (Kulkarni et al., 2010; Bennett et al., 2015). Hence, soil compaction and subsoil impact are of concern to continued cotton production (Antille et al., 2016). This work focusses on the Australian industry as a case study, and therefore limits the scope of discussion to the JD7760. Irrespective of machine make, it is the soil surface stress that is of relevance.

Despite the JD7760 being fitted with dual tires on the front axle, subsoil stresses are comparable to commercially available combine harvesters reported by Chamen (2015), and well in excess (approaching 300%) of the heavy machinery definition (Braunack and Johnston, 2014; Roberton and Bennett, 2017). The mass of the JD7760 ranges from 32 Mg (field ready starting weight) to 36.5 Mg (fully laden; i.e. carrying two modules), which is approximately a 50% increase in mass from the previous cotton harvesting system. The mass over the rear axle increases from 10.6 to 12.8 Mg during module building, and then from 14.5 to 16.5 Mg as it creates a second module and carries the first module in a basket at the rear of the machine (Bennett et al., 2015), and is spread over two wheels. The front axle mass is approximately static at 21.5 Mg, with axle load spread over four wheels in a dual wheel configuration. This increase in mass and large traffic footprint has resulted in soil compaction down to 0.8 m depth (Bennett et al., 2017; Braunack and Johnston, 2014; Roberton and Bennett, 2017), as well as associated yield penalties (Bartimote et al., 2017) within the Australian cotton system. Given the extent of use of such heavy machinery and the likelihood for impact to the soil resource, there is requirement to better understand the breadth of effect and inform guidelines for safe traffic. Therefore, the aim of this work was to assess soil compaction extent with depth throughout the industry, as well as to inform traffic management options. Both topsoil and subsoil compaction were assessed in order to understand the risk of unchanged traffic management.

2. Methodology

Seven experimental sites (Table 1) were utilised to assess the soil compaction impact of the John Deere 7760 (JD7760). The sites came from the Macquarie, Border Rivers and Darling Downs catchments, but represented the major cotton growing soil, primarily Grey Vertisols and Black Vertisols (IUSS Working and Group, 2014), with temperate climatic condition. Sites were selected on the basis of traffic history so that a range of histories could be assessed. Due to the rapid adoption of the JD7760, the choice of sites where it had not been used prior to 2012 was extremely limited. The experimental sites Warren and Jimbour had never experienced any JD7760 traffic before and at the time of measurement. Whilst Jimbour and Bongeen were dryland farms, the soil was experimentally irrigated for the assessments at Jimbour, and, for Bongeen, experiments were carried out on a stored moisture profile representative of the soil moisture status at harvest over irrigated soils. Hence, at the time of traffic all sites were considered representative of an irrigated soil, and the moisture content at time of traffic is reported.

2.1. Experimental design

The experiment was designed to provide a snapshot of the extent of impact the JD7760 has caused since inception in the industry. From the seven sites, three would provide a first impact assessment, whilst the other four provided a cumulative impact assessment with varying years of traffic (Table 1). Sampling was conducted before and after the soil was subject to cotton picking traffic to determine changes in soil moisture content distribution and bulk density. As the density of Vertisols changes with moisture content, the before condition provided the reference for density change; i.e. no moisture was lost or added between the traffic events. Fig. 1 shows the wheel configuration of the machine corresponding to sampling approaches.

2.2. SoilFlex modelling

SoilFlex (Keller et al., 2007) was used to simulate soil vertical stress distribution under the wheels. Simulations were conducted assuming an elliptical contact area, standard tyres and manufacturer's recommended inflation pressures. For the JD7760: 520/85R42-R1 and 520/85R34-R1 for standard dual (front) and rear axles, respectively; inflation pressures were 0.25 MPa (front) and 0.32 MPa (rear). For the JD9996: 20.8–42 14PR-R1 (front duals) and 14.9–24 12PR-R2 (rear), with inflation pressure of 0.25 MPa (front) and 0.29 MPa (rear). The JD9996 has historically, and commonly, been used with single tyres at the front, so this was also modelled using 20.8–42 14PR-R1 (front) with inflation pressure of 0.29 MPa; the rear configuration was as above.

2.3. Soil sampling

Soil sampling occurred at stations (Fig. 1), before and after traffic. Sampling transects were constructed so that the furrow under the centre line of the machine (termed the diff furrow) through to the outer non-traffic furrow were investigated. Two replicates within 1.0 m of each other within the same furrow were taken at each station (Fig. 1). Two stations were investigated for each property.

A total of 16 cores (coring tube internal diameter of 47.5 mm and 1000 mm in length) per sampling incidence were taken before and after traffic. The sampling depth was 0.8 m to coincide with the maximum

Table 1
Experimental sites, region and location with traffic history prior to soil compaction assessment; "traffic" refers to previous cotton system machinery traffic immediately preceding the introduction of the JD7760; "JD7760 traffic" refers to a single pass in each year recorded; and, "no-traffic" refers to the length of time a field had been CTF without a wheel having passed that are of the paddock.

ID	Region	Catchment	Traffic history	Soil	Location
A	Toobeah	Border Rivers	11 yrs traffic, 2 yrs JD7760	Grey Vertisol	28°30'4.54"S, 149°45'37.23"E
B	Goondiwindi	Border Rivers	22 yrs traffic, 8 yrs ago traffic lines changed, and 5 yrs ago changed to 12 m system, 2 yrs JD7760	Grey Vertisol	28°37'26.62"S, 150°32'23.47"E
C	Yelarbon	Border Rivers	23 yrs of traffic, 2 yrs of JD7760	Grey Vertisol	28°27'39.00"S, 150°10'19.67"E
D	Warren	Macquarie	24 yrs of traffic, bio-ripped, field reformed, no JD7760	Grey Vertisol	31°47'24.15"S, 147°44'4.68"E
E	Jimbour	Darling Downs	30 yrs of traffic, no JD7760	Black Vertisol	27°30'23.9"S, 151°27'49.5"E
F	Bongeen	Darling Downs	15 yrs no-traffic, no JD7760	Black Vertisol	26°57'35.26"S, 151° 7'4.46"E
G	Aubigny	Darling Downs	30 yrs of traffic, 4 yrs of JD7760	Black Vertisol	27°28'30.44"S, 151°37'41.27"E

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