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Effect of cattle trampling and farm machinery traffic on soil compaction of an *Entic Haplustoll* in a semiarid region of Argentina

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Abstract. Soil compaction has detrimental effects on the physical, mechanical and hydraulic properties of soils, and affects important soil processes and function, and crop productivity. This work was conducted to investigate soil compaction impacts in integrated arable cropping-livestock systems managed under conventional tillage (CT) and no-tillage (NT). The work examined the combined effects of cattle trampling and farm machinery traffic on: soil strength, soil deformation, and water infiltration into soil. The following treatments were applied to soil (*Entic Haplustoll*, 60% sand) managed under CT and NT: three traffic intensities (1, 5, 7 passes) performed with light (2WD, 53 kN) and heavy (4WD, 100.4 kN) tractors, and two stocking densities (400 and 700 kg ha^{-1}), respectively. Controls were also used to represent the condition of the soil without any effect of livestock or field traffic. In both tillage systems, soil penetration resistance (strength) increased and water infiltration into soil decreased as traffic intensities or stocking rates applied increased. There was a significant traffic intensity × stocking rate interaction, which influenced the depth and extent of soil compaction at depth. Despite these results, stubble grazing during fallow should not be discouraged as this practice offers mixed farming systems several agronomic and financial benefits. If stubble was to be grazed, the system would need to be carefully managed: (1) avoid 'random' traffic using permanent or semi-permanent traffic paths to minimise the field wheeled area, (2) vacate livestock from the field, or confine it to a sacrificial area, when the soil water content exceeds a critical level above which soil damage is likely, and (3) maintain more than 60%–70% ground cover. Tillage repair treatments can be targeted to those sacrificial or 'hot-spots' areas so that localised, as supposed to widespread, compaction problems are rectified before the next crop is established.

Key words: axle load, cone index, ground cover, infiltration, soil deformation, traffic intensity.

INTRODUCTION

The western Pampas region of Argentina contributes a significant proportion of the country's agricultural production, including beef, dairy and arable cropping. The region comprises of approximately 8 M ha and is characterised by a semiarid climate. The mean annual rainfall is about 500 mm of which 75% falls between October and April. About 1.1 M ha of this land are used for arable cropping and is dominated by *Haplustoll* soils (INTA, 2009). Over the past 30 years, growers have progressively transitioned from conventional tillage (CT) to no-tillage (NT) systems, with the dual purpose of improving soil and water conservation and crop reliability, and as a result, be able to reduce financial risks and costs. The development of high-yielding GM crops, purposely-designed NT technology and sustained on-farm research effort have greatly enabled this transition (Peiretti & Dumanski, 2014). The net result has been a significant increase in crop productivity, facilitated by improved timeliness of field operations (planting, spraying, harvesting) and the use of farm equipment with increased capacity. However, a drawback of this process has been the progressive increase in machinery power, and consequently weight. Up to the early 1990's, the median size of a tractor in the region was 90 kW, which compares with 260 kW tractors commonly used at present. Such a shift in machinery size is also explained by the fact that key operations (e.g., spraying, harvest) are performed by contractors who rely on high-capacity equipment to remain profitable. Increased machinery weight has led to increased risk of soil damage due to compaction, particularly in the subsoil (e.g., ≥ 350 mm deep) (Chamen, 2015). Despite the seasonality of (summer) rainfall in this region, wet conditions at harvest, that is early autumn for summer-grown crops, are not uncommon, which means that the risk of compaction occurring is relatively high most years. The occurrence of soil compaction in this region is fairly well documented and has been attributed to a combination of tillage and traffic in some of the early work (e.g., Panigatti, 1964; Quiroga et al., 1999) and traffic in more recent studies (e.g., Botta, et al., 2019a; 2002).

Compaction adversely affects the physical and hydraulic properties of soils, and the ability of crops to efficiently use water (rainfall, irrigation) and applied nutrients; thus, reducing fertiliser recovery in grain and crop productivity (Soane & van Ouwerkerk, 1995; Hussein et al., 2018). Botta et al. (2004) showed that the yield of soybean (*Glycine max* L., Merr) crops established under NT decreases with increased soil compaction, and that yield penalties are proportional to the traffic intensity applied to the soil. Traffic intensity is determined by the combined effect of number of passes with a given farm vehicle over a given area and its overall load (Mg km^{-1} ha^{-1}). Botta et al. (2004) reported yield penalties of up to 38% compared with crops grown for three consecutive years on untrafficked soil. Deep compaction (≥ 350 mm) is often explained by the effect of traffic with high axle loads whereas shallower compaction is due to the pressure exerted at the soil-tyre contact area (e.g., Etana & Håkansson, 1994; Håkansson & Reeder, 1994; Botta et al., 2006a, 2006b). More recent studies (e.g., Ansorge & Godwin, 2007; Antille et al., 2013; Botta et al., 2019b) have also shown that while load is important, more so is how that load is spread over the contact area. Developments in low ground pressure systems, such as 'Hi-Flex' tyres and rubber belt technology, offer promise to mitigate compaction impacts associated with high axle loads (e.g., Ansorge & Godwin, 2008; Godwin et al., 2015; Desbiolles et al., 2019).

In CT systems, the load-carrying capacity of the soil is typically low; consequently, a single pass of a farm vehicle can cause up to about 80% of the maximum compaction and up to 90% of the maximum rut depth (Inns & Kilgour, 1978; Taylor et al., 1982). The initial soil strength is the main factor influencing the response of the soil to external stresses that are applied to that soil (Paz & Guérif, 2000). By contrast, soils under long-term NT generally exhibit greater load-carrying capacity than CT soils, because of natural consolidation in the absence of tillage as well as compaction caused by field traffic (Carter, 1990; Botta et al., 2010). In NT systems with stubble-grazing, relatively shallow compaction (e.g., $\leq$ 200 mm) has also been attributed to the effect of cattle trampling (e.g., Tollner et al., 1990; Fernández et al., 2011), but some studies have shown that the overall effect is negligible (e.g., Franzluebbers & Stuedemann, 2008). In rigid soils, such as those that occur in the region of interest to this study, subsoil compaction may be regarded as 'permanent' because of its long-term persistence (Arvidsson, 2001). The absence of natural processes such as swelling-shrinking or freezing-thawing cycles means that subsoil compaction cannot be easily reverted and amelioration through tillage is often required (Pollard & Webster, 1978; Dexter, 1991).

There appears to be a paucity of scientific information about the extent and degree of soil compaction in CT and NT systems of the western Pampas of Argentina; particularly, for systems that integrate arable cropping with stubble grazing during the fallow period. Potential soil impacts associated with stubble grazing during the winter fallow, which is commonly practiced in this region, are not well documented. Further, the few studies available appear to be outdated as they have been conducted with much lighter farm equipment, which are no longer used. The work reported in this article aims to inform the development of best soil and stubble management practices relevant to integrated arable cropping-livestock systems. This requires that potential impacts on soil associated with field traffic and stubble grazing be quantified so that appropriate intervention measures, such as controlled traffic and occasional tillage (e.g., Melland et al., 2017; Dang et al., 2018), can be undertaken, and that timing of stubble grazing and stocking rates (e.g., Swan et al., 2018) can be optimised. The dataset provided by this study can be used to inform the selection of appropriate farm machinery (size, capacity) with a view to minimising impacts on soil. As such, this study was undertaken to address this apparent lack of information by conducting a set of field observations that involved measurements of key soil physical/mechanical and hydraulic properties. Measurements were undertaken before and after compaction treatments were applied using a factorial combination of traffic intensities and stocking rates. Treatments were selected to represent common management practices in the region. It was hypothesised that the impact of traffic and stubble grazing on soil compaction would occur to lesser extent in soils managed under long-term (e.g., > 10 years) NT compared with soils managed under CT, but the overall effect would be significant in both soils.

MATERIALS AND METHODS

Site description

The study was conducted in a commercial farm located in Trenque Lauquen, Argentina (36°04'33" S, 62°29'14" W, 300-m above-sea level). The soil is classified as *Entic Haplustoll* (USDA Soil Taxonomy). Surface runoff at the site is negligible as the soil has a gentle slope (<1%) and is well-drained with moderately high permeability.

Soil textural analyses (Bouyoucos, 1962) for the 0–150 mm and 150–450 mm depth intervals reported 565 and 583 g kg^{-1} sand (50–500 µm), 274 and 239 g kg^{-1} silt (2–50 µm), and 161 and 178 g kg^{-1} clay (< 2 µm), respectively. Analysis of soil organic carbon (Walkley & Black, 1934) showed 12.3 g kg^{-1} and 5.85 g kg^{-1} SOC for the 0–150 mm and 150–450 mm depth intervals, respectively. A full description of the soil profile (0–1200 mm) is given by Botta el al. (2019a).

Experimental

A description of the two tractors used in the study is shown in Table 1. The mean pressure at the soil-tyre contact area was measured using a Tekscan® sensor (Tekscan, Inc., www.tekscan.com) and resulted from fifteen data points (n = 15) taken for each of the tractor tyres. The tyre inflation pressure was adjusted based on the manufacturer's recommendation for load and speed, and the tractors were operated at 8 km h^{-1}.

Table 1. Specification of tractors used in the experiments

Tractor, Unit	John Deere 4730
Drivetrain	2WD
Engine power (IRAM8005), HP	102
Tractor weight, kN	53
Weight (rear axle), kN	36
Weight (front axle), kN	17
Front tyres	10.00×16
Inflation pressure (front tyres), kPa	170
Rear tyres	23.1R30
Inflation pressure (rear tyres), kPa	130
Tractor, Unit	Zanello 540
Drivetrain	4WD
Engine power (IRAM8005), HP	210
Tractor weight, kN	100.4
Weight (rear axle), kN	34.28
Weight (front axle), kN	65.72
Front tyres	18.4R34
Inflation pressure (front tyres), kPa	140
Rear tyres	18.4R34
Inflation pressure (rear tyres), kPa	140

The following soil properties were measured: (1) soil strength was determined with the use of an electronic cone penetrometer (FieldScout SC-900), which automatically recorded the force to a depth of 450-mm at regular increments of 25-mm, based on ASABE (2019). Measurements (n = 20 per plot) were conducted immediately after the traffic and stocking rates treatments were applied and followed a similar approach to that used by Smith and Dickson (1990), albeit with livestock as an added factor. Control plots were also used to allow the undisturbed soil condition to be determined, that is, without the traffic × livestock effect; (2) measurements of water infiltration into soil (n = 3 per treatment) were conducted using the double-ring infiltrometer (Parr & Bertrand, 1960), readings taken at 125 minutes after the infiltration test was initiated (t = 125 min) and reported; (3) rut depth was measured using a profile-meter; and (4) soil water content was also determined because of its effect on soil strength (Ayers & Perumpral, 1982; Aikins et al., 2019, 2020). For this, soil samples (n = 20 for each depth interval) were taken at regular depth intervals (0–150, 150–300, and 300–450 mm, respectively), and subsequently oven-dried at 105 ± 5 °C for 48–72 hours (MAFF, 1986).

Traffic treatments were applied to two plots in which the soil had been managed under continuous (> 10 years) conventional tillage (CT) and no-tillage (NT), respectively. The crop grown at the site had been maize (*Zea mays* L.), which has a dual purpose; after the grain is harvested in autumn, the stubble is grazed by cattle over the fallow time in winter. The traffic treatments consisted of three different traffic intensities that combined number of tractor passes (1, 5, 7, respectively) with vehicle weight (Table 1), and replicated controls. A complete factorial arrangement with three replications per treatment ($n = 3$) was established using 48, 50-m×50-m plots. Measurements of water infiltration into soil and penetration resistance were conducted before and after traffic and stocking rate treatments were applied. For both determinations, the 'after' measurements were conducted at the centreline of the tyre rut where changes in soil properties, relative to the 'before' condition, were expected to be greatest. Soil-tyre contact stresses tend to concentrate toward the centreline of the rut (Way et al., 1997; Antille et al., 2013). After the harvest operation was completed, and the traffic treatments applied, two stocking rates were imposed to both CT and NT plots, and these are referred to here as low (400 kg ha^{-1}) and high (700 kg ha^{-1}), respectively. To achieve these stocking rates, the number of animals per plot remained constant, but the area within each plot was adjusted by using an electric fence. The animals were allowed to consume the stubble until ground cover dropped to about 60%, consistent with standard agronomic practice. Thus, the amount of dry matter retained on the plots ensured a 'safe' level of ground cover that was required to reduce the risk of wind erosion (Mendez & Buschiazzo, 2015). Subsequently, the animals were removed from the plots. Each plot had an area that could not be entered by animals used as control.

Summary of experimental design: The final experimental design resulted from a factorial combination of the following treatments: two tillage management systems (CT: conventional tillage and NT: no-tillage), six traffic intensities given by light (2WD, 53 kN) and heavy (4DW, 100.4 kN) tractors and number of tractor passes (1, 5 and 7), and two stocking rates (low: 400 kg ha^{-1} and high: 700 kg ha^{-1}), respectively. Controls (zero-traffic, zero-stocking rate) were also used both in the conventional and no-tillage systems, respectively. All treatments were replicated three times ($n = 3$), which therefore resulted in 96 experimental plots.

Statistical analyses

Statistical analyses were undertaken with STATGRAPHICS 7.1® (www.statgraphics.com), and involved analysis of variance (ANOVA), which was applied to all measured variables. Mean treatment effects from the tillage system × traffic intensity × stocking rate combinations were determined by applying the Duncan test using a probability level of 1% ($P < 0.01$) (Little & Hills, 1978).

RESULTS AND DISCUSSION

Table 2 shows measurements of soil water content recorded at the time the treatments were applied to the CT and NT soils. Results showed that overall differences in soil water content were not significant ($P > 0.01$); therefore, values of penetration resistance were not corrected by soil water content (Unger, 1996; ASABE, 2019). Table 3 shows that the contact pressure measured in CT soil was less than that of NT soil ($P < 0.01$), consistent with measurements of rut depth (Table 6). Softer soil conditions in CT compared with NT resulted in greater soil deformation thus increasing the area and dimensions of the part of the tyre in contact with the ground ('contact patch') (Burt et al., 1987; Way et al., 2005). This reduces the (average) contact pressure under the tyre despite the fact that, at the same load and inflation pressure, tyre deflection may be concurrently reduced (Raper et al., 1995a; Misiewicz et al., 2015). Hence, under relatively soft soil conditions such as those of the CT soil, tyre inflation pressure may be reduced slightly compared with the recommended pressure for the same load on a firmer soil condition (Raper et al., 1994; 1995b). This will also help reduce rolling resistance and improve traction (Wood & Burt, 1987; Ejsmont et al., 2016; Luhaib et al., 2017).

Table 2. Gravimetric water contents (θ_g) recorded at the site at the time the experiments were conducted. Mean values ± standard deviation ($n = 20$). Based on the Duncan test, letters show that mean values are not statistically different at a 1% probability level

Tillage system	Conventional tillage	No-tillage
Depth interval (mm)	$\theta_g (\%, w/w)$	$\theta_g (\%, w/w)$
0–150	13.2 ± 1.71a	7.2 ± 1.60a
150–300	10.3 ± 1.67a	9.1 ± 1.54a
300–450	9.5 ± 1.52a	8.3 ± 1.47a

Table 3. Mean contact pressure recorded at the soil-tyre interface ($n = 15$) for the two tractors used in the experiments. Values are given in kPa

Tyre, tillage system	John Deere 4730	Zanello 540
Front tyre, conventional tillage	74.7	49.0
Front tyre, no-tillage	100.3	57.8
Rear tyre, conventional tillage	38.9	30
Rear tyre, no-tillage	43.2	33.4

For the control soils, differences in water infiltration rates between CT and NT were significant ($P < 0.01$). At $t = 125$ min, mean infiltration rates were 90 and 55 mm h^{-1} for CT and NT, respectively. Overall, and before the treatments were applied, NT soil showed significantly higher values of penetration resistance up to a depth of 375 mm ($P < 0.01$), which reflected increased soil carrying capacity compared with CT soil (Fig. 1). At greater depths, differences between the two soil conditions were non-significant ($P > 0.01$).

Penetration resistance in CT soil peaked at 250 mm deep where it exceeded the suggested 2,000 kPa threshold (Taylor & Ratliff, 1969a, 1969b) above which root elongation may be significantly affected. Increased soil strength at this depth also suggested a plough pan was present, likely as a result of tillage operations conducted consistently at the same depth, and over a relatively long period of time (Cresswell et al., 1992). Below that depth, values of penetration resistance declined a little, but they remained around the 2,000 kPa range throughout the profile. In NT soil, values of penetration resistance peaked at a 200 mm deep (≈ 4,250 kPa) and declined to about

2,500 kPa or less below 250 mm deep suggesting that this soil may benefit from occasional or 'strategic' deep tillage (Spoor & Voorhees, 1986; Dang et al., 2018).

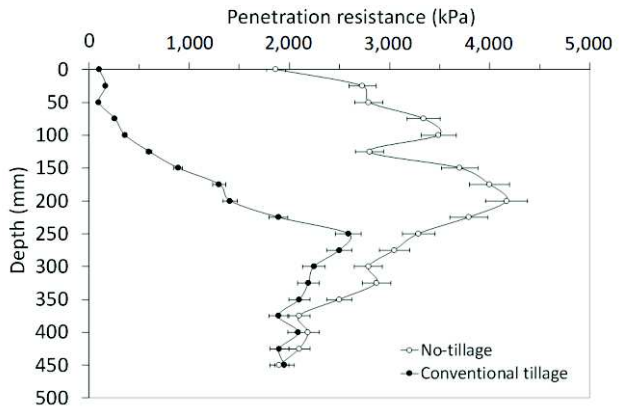

Figure 1. Soil penetration resistance recorded at the experimental site before the traffic and stocking rate treatments were applied. Error bars on mean data points (n = 20) denote the standard deviation.

A summary of soil penetration resistance, water infiltration rates, and rut depth measurements for all combinations of traffic intensities and stocking rates is shown in Tables 4–6. In both tillage systems, penetration resistance data showed that the depth and extent of soil compaction increases with the number of passes and axle load. A single pass of the heavier tractor used in this study was sufficient to cause compaction to the full measured depth. The lighter tractor required five or more passes. At shallow depths (≤ 150 mm), compaction was always significant regardless of the number of passes or the weight of the tractor. Pulido-Moncada et al. (2019) showed that the degree of soil compactness can be higher than 95% if multiple passes (e.g., 4–5) with 3–5 Mg wheel loads are performed. Measured pressures at the soil-tyre contact area in this study were slightly higher than the maximum value recommended by Alakukku (1996) for prevention of soil compaction. Maximum wheel loads have been suggested (e.g., Håkansson & Petelkau, 1994; van den Akker, 1998) in attempts to limit compaction to relatively shallow depths, but such limits can be easily exceeded with current editions of farm machinery. Technical solutions are available (e.g., Soane et al., 1982) including low (ground) pressure tyre technology and controlled traffic farming (e.g., Antille et al., 2015, 2019; Bluett et al., 2019), which have been shown to be cost-effective (e.g., Chamen et al., 2015; Godwin et al., 2015; Galambošová et al., 2017).

Water infiltration into soil was significantly affected by compaction in all treatments (Table 5), and the effect was proportional to the traffic intensity and stocking rate applied, which was consistent with other studies on light soils (e.g., Usman, 1994; Chyba et al., 2014; Ngo-Cong et al., 2020). This is an important practical consideration for water conservation in semiarid regions, such as the western Pampas, that rely on rainfall and soil water storage for successful crop establishment.

Table 4. Mean values (n = 20) of soil penetration resistance (kPa) recorded after traffic and stocking rate treatments were applied to soil managed under conventional tillage and no-tillage. Different letters (horizontally and within the same stocking rate) indicate that mean values are significantly different at a 1% probability level based on the Duncan test

Tillage system	Conventional tillage							
Tractor	John Deere 4730							
Stocking rate	700 kg ha^{-1}				400 kg ha^{-1}			
Depth (mm), Traffic	1 Pass	5 Passes	7 Passes	Control	1 Pass	5 Passes	7 Passes	Control
0–150	1,590*b*	1,801*c*	1,953*d*	889*a*	1,330*b*	1,421*b*	1,677*c*	695*a*
150–300	2,443*b*	2,410*b*	2,627*c*	2,190*a*	17,91*b*	1,811*c*	2,114*d*	1,460*a*
300–450	2,527*a*	2,595*a*	2,748*b*	2,500*a*	2,024*a*	2,110*b*	2,423*c*	1,992*a*
Tractor	Zanello 540C							
Stocking rate	700 kg ha^{-1}				400 kg ha^{-1}			
Depth (mm), Traffic	1 Pass	5 Passes	7 Passes	Control	1 Pass	5 Passes	7 Passes	Control
0–150	1,910*b*	2,357*c*	2,500*d*	889*a*	1,710*b*	1,829*c*	2,201*d*	695*a*
150–300	2,500*b*	2,660*c*	2,810*d*	2,190*a*	2,145*b*	2,368*c*	2,619*d*	1,267*a*
300–450	2,801*b*	2,929*c*	2,921*c*	2,500*a*	2,300*b*	2,502*c*	2,834*d*	1,992*a*
Tillage system	No-tillage							
Tractor	John Deere 4730							
Stocking rate	700 kg ha^{-1}				400 kg ha^{-1}			
Depth (mm), Traffic	1 Pass	5 Passes	7 Passes	Control	1 Pass	5 Passes	7 Passes	Control
0–150	3,288*b*	3,803*c*	3,970*d*	3,110*a*	2,940*b*	3,123*b*	3,478*c*	2,812*a*
150–300	3,735*a*	3,821*a*	4,127*b*	3,791*a*	3,145*a*	3,200*a*	3,600*b*	3,791*a*
300–450	2,830*a*	2,888*a*	2,902*a*	2,821*a*	2,778*a*	2,791*a*	2,900*a*	2,710*a*
Tractor	Zanello 540C							
Stocking rate	700 kg ha^{-1}				400 kg ha^{-1}			
Depth (mm), Traffic	1 Pass	5 Passes	7 Passes	Control	1 Pass	5 Passes	7 Passes	Control
0–150	3,299*b*	3,890*c*	4,110*d*	3,110*a*	3,156*b*	3,300*c*	3,432*d*	2,812*a*
150–300	4,002*b*	4,133*b*	4,318*c*	3,791*a*	3,897*b*	3,933*b*	3,990*c*	3,791*a*
300–450	3,133*b*	3,254*b*	3,634*c*	2,821*a*	3,102*b*	3,119*c*	3,401*d*	2,821*a*

Table 5. Mean values (n = 3) of water infiltration into soil (mm h^{-1}) measured at t = 125 min after traffic and stocking rate treatments were applied to soil managed under conventional tillage and no-tillage. Different letters (vertically) indicate that mean values are significantly different at a 1% probability level based on the Duncan test

Tillage system	Conventional tillage				No-tillage			
Stocking rate	400 kg ha^{-1}				400 kg ha^{-1}			
Tractor, Traffic	Control	1 Pass	5 Passes	7 Passes	Control	1 Pass	5 Passes	7 Passes
Zanello 540	90*a*	54*a*	31*a*	17*a*	55*a*	32*a*	24*a*	13*a*
John Deere 4730	90*a*	71*b*	38*b*	32*b*	55*a*	43*b*	37*b*	31*b*
Stocking rate	700 kg ha^{-1}				700 kg ha^{-1}			
Tractor, Traffic	Control	1 Pass	5 Passes	7 Passes	Control	1 Pass	5 Passes	7 Passes
Zanello 540	90*a*	40*a*	28*a*	15*a*	55*a*	29*a*	22*a*	8*a*
John Deere 4730	90*a*	61*b*	33*b*	26*b*	55*a*	45*b*	31*b*	24*b*

Table 6. Maximum rut depth (mm) measured at the centreline of the tyre rut after traffic treatments were applied to soil managed under conventional tillage and no-tillage. Mean values ± standard deviation (n = 3). Different letters (vertically) indicate that mean values are significantly different at a 1% probability level based on the Duncan test

Tillage system	Conventional tillage			No-tillage		
Tractor, Traffic	1 Pass	5 Passes	7 Passes	1 Pass	5 Passes	7 Passes
Zanello 540	44.4 ± 4.2*a*	39.2 ± 3.2*a*	45.3 ± 3.0*a*	20.0 ± 1.2*a*	23.1 ± 2.1*a*	24.0 ± 1.5*a*
John Deere 4730	40.2 ± 3.7*a*	38.7 ± 2.9*a*	42.3 ± 3.1*b*	8.5 ± 8.5*b*	10.1 ± 1.7*b*	7.30 ± 1.7*b*

Overall, soil mechanical and hydraulic responses to livestock grazing stubble showed detrimental effects in both tillage systems. The impact was greater on CT because of significantly lower soil strength and soil carrying capacity compared with NT. However, stubble grazing may not be discouraged as it offers mixed farms a 'low cost' cattle feed at a time of the year when other sources of forage are more expensive (e.g., winter cover crops) or not readily available. Winter cover or dual-purpose crops will tend to reduce plant available water for the subsequent summer crop (e.g., maize) and will likely have an impact on yield. By contrast, stubble grazing can have no significant impact on soil water availability for the following crop in the rotation, provided livestock was carefully managed. This requires that a minimum of 60% to 70% ground cover, or about 2–3 Mg ha^{-1} of stubble, is retained to ensure the soil is protected from erosion and evaporative losses are minimised (Swan et al., 2018). To minimise the risk of soil damage due to compaction, livestock should be removed from the field when the soil water deficit (SWD) declines below a critical level. This critical SWD should ensure livestock compaction is negligible or only confined to very shallow depths (e.g., ≤ 75 mm) so that it can be removed by the sowing operation without causing any impact on crop establishment. Similar approaches have been satisfactorily used to establish SWD thresholds for limits to trafficability with farm equipment (e.g., Earl, 1997; Vero et al., 2014), and these could be adopted for integrated arable cropping-livestock systems.

CONCLUSIONS

This article has presented and discussed results derived from field investigations that were conducted to quantify soil compaction impacts in integrated arable cropping-livestock systems. Results can be used to inform the development of best soil and stubble management practices in those systems.

Soil compaction occurred to lesser extent in soil managed under long-term (10 years) no-tillage (NT) compared with soil managed under conventional tillage (CT), but the overall effect of compaction was significant in both soils. This observation confirmed the hypothesis formulated prior to this study. This work also showed that soil compaction was higher with increased traffic intensities or stocking rates. There was a significant traffic intensity × stocking rate interaction, which influenced the depth and extent of compaction at depth. Despite these results, stubble grazing during winter fallow should not be discouraged as this practice offers mixed farming systems several tangible benefits, including agronomic and financial. If stubble was to be grazed, the system would need to be carefully managed: (1) avoid 'random' traffic using permanent or semi-permanent (seasonal) traffic paths that minimise the wheeled area within the field, (2) vacate livestock from the field, or confine it to a sacrificial area within the field. This may be performed when the soil water deficit reaches a critical level below which the risk of soil damage due to compaction (reduced bearing capacity) is significant. This should also ensure that compaction is limited to very shallow depths and that it can be removed by the sowing operation without affecting crop establishment, and (3) maintain no less than 60%–70% ground cover (stubble retention) to reduce the risk of erosion and evaporative losses.

Tillage repair treatments can be targeted to those sacrificial or 'hot-spots' areas so that localised, as supposed to widespread, compaction problems are rectified before the next crop is established.

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