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Effects of Grazing Sorghum Stubble on Soil Physical Properties and Subsequent Crop Performance

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Abstract: Two grazing trials were conducted on a Vertosol in central Queensland to assess the effects of stubble grazing by cattle on soil properties and subsequent crop performance. Two adjacent contour bays were selected for two treatments (grazed and ungrazed) in each trial. Both trials were conducted following a grain sorghum crop. In trial 1 (during 1996) the surface soil was dry throughout grazing. In trial 2 (during 1998) the surface soil became saturated during grazing after 125 mm of rain. Soil physical properties including bulk density, shear strength, cone index and hydraulic conductivity were measured pre-and post-grazing in both trials and the response of wheat crops sown after grazing was assessed. The area was then double-cropped to sorghum to measure any further residual impacts. After grazing on dry soil, hoof marks were barely evident and no significant change was found in any soil physical property or the establishment or yield of a subsequent wheat crop. After grazing on saturated soil, there were visible hoof marks 49 mm deep and increases in soil shear strength, cone index and drawbar power requirement. The following wheat crop had reduced dry matter at 32 days and reduced grain yield. There was no immediate change in ground cover and no effect on wheat establishment following direct-drilling 37 days after the cattle were removed. In a sorghum crop following the wheat crop, there were no carryover effects on any soil physical property or on crop yield. We conclude that under a similar regime to that of trial 1 (dry soil and no rainfall during grazing), adverse effects of stubble grazing are unlikely. It follows that if grazing can be restricted to times when the surface soil is dry enough to minimise compaction by animals, there is little risk of adverse effects on subsequent crop performance.

Key words: Beef cattle, brigalow, crop yield, soil compaction, central Queensland

INTRODUCTION

Stubble grazing becomes necessary for mixed farming enterprises (cattle and grain properties) in central Queensland at times of feed shortages or drought. Grain sorghum (*Sorghum bicolor*) is the preferred summer crop for these enterprises because under dry seasonal conditions a failed crop or the residues of a successful crop can be used to provide valuable feed for cattle. Producers have expressed concern, however, that grazing cattle may compact the soil, resulting in delayed sowing (to prepare a seedbed) and reduced yield of subsequent crops. A further concern is that removal of the stubble by the grazing cattle will leave the soil exposed to raindrop impact, reducing rainfall infiltration and soil water storage.

The ground pressure exerted by cattle is comparable to the pressure under agricultural tractors[14]. The static hoof pressure of cattle is 98-192 kPa compared with 74-81 kPa for unloaded tractors[8]. When the animal is moving, pressures are higher as its weight is on only 2 or 3 hooves and kinetic energy is involved[8]. Since the depth of influence below the soil surface of a given contact pressure increases with the width of the applied stress, the compactive effect of grazing livestock is shallower than for vehicles[8].

Sheep have been shown to cause soil compaction on a silty loam in Victoria[23] even though their static

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hoof pressure (60-80 kPa) is about half that of cattle[14]. Long-term grazing by cattle has compacted clay loams and sandy loams to a depth of 25 mm[1], a silt loam to 400 mm[11] and a loamy fine sand to 900 mm[20]. Cattle grazing has restricted water movement into and through the soil profile, especially during rainstorms[11]. This effect can be attributed to both compacted soil and reduced vegetation cover. New Zealand studies have shown that cattle grazing pastures on sloping land contribute to runoff, soil erosion and loss of nutrients[12].

Soil recovery after cessation of heavy cattle grazing and trampling took up to four years for two silt loams and a sandy loam in South Dakota[13]. At least 16 months of stock exclusion were required to obtain measurements similar to the original ungrazed site after grazing cattle increased clod bulk density in the surface 50 mm of a loam in south west Idaho[21].

There is abundant published information on the effects of cattle grazing and trampling on pastoral land but little has been published on the effects on cropping land. The aim of this study was to assess the impact of grazing cattle on the soil physical properties of cropping land and on the establishment, growth and yield of subsequent crops in the semi-arid environment of central Queensland.

MATERIALS AND METHODS

Site: The trial site was located at the Brigalow Research Station in central Queensland, Australia (24.81°S, 149.80°E, altitude 151 m). Prior to clearing in 1982, brigalow (*Acacia harpophylla*) and belah (*Casuarina cristata*) dominated the native forest. The soil is an association of grey and black Vertosols[10] with a land slope averaging 2.5%. The climate is semi-arid to sub-humid and subtropical, with median annual rainfall of 665 mm and mean annual potential evaporation of 2200 mm (Class A pan).

Design: Two adjacent contour bays, each 0.8 ha in area, were selected for the two treatments: ungrazed and grazed by cattle. Treatment replication was not feasible because large areas are necessary to avoid localised trampling effects (such as from camp sites and cattle pads) and the availability of experimental animals was limited. However, the experimental site was selected because management had been the same in both bays and accurate records of crop establishment and yield data were available. These records showed a consistent pattern of establishment and yield in each bay from six earlier grain crops, which provided a measure of the inherent variability between the bays and an indication of their expected future performance.

Two trials were conducted - trial 1 in 1996 and trial 2 in 1998. The same bay was grazed in each trial and this was the only difference between the two bays in management treatments. Grazing commenced 47 and 69 days after harvesting sorghum in trials 1 and 2, respectively. Wheat (*Triticum aestivum*) was then sown 58 and 36 days after the cattle were removed and sorghum was sown 15 and 19 days after the wheat harvest, in trials 1 and 2, respectively.

Trial 1 (1996): A sorghum (cv. MR51) crop was harvested on 24 Jan 1996 prior to the start of the trial. The control bay was sprayed on 13 Feb 1996 with paraquat (270 g ha^{-1}) + diquat (230 g ha^{-1}) to control sorghum regrowth while the grazed bay was stocked with 10 Brahman-cross (*Bos indicus* x *Bos taurus*) beef cattle (12.5 head ha^{-1}) for 15 days from 11 to 26 Mar 1996 (150 animal grazing days). Rainfall before and during grazing was negligible, so the surface soil was dry throughout the grazing period. After grazing, both bays were sprayed with glyphosate trimesium (900 g ha^{-1}) + oxyfluorfen (18 g ha^{-1}) on 16 May 1996 in preparation for wheat sowing. Wheat (cv. Hartog) was sown with a zero-till planter in 275 mm rows on 23 May 1996 at a seeding rate of 31 kg ha^{-1} and harvested on 31 Oct 1996. In-crop rainfall was 186 mm. Sorghum (cv. MR31) was then sown on 15 Oct 1997 and harvested on 21 Jan 1998 in both bays.

Trial 2 (1998): A sorghum (cv. MR31) crop was harvested on 22 Jan 1998 prior to the start of the trial. The control bay was sprayed with glyphosate (900 g ha^{-1}) + oxyfluorfen (18 g ha^{-1}) on 19 Mar 1998 to control sorghum regrowth while the grazed bay was stocked with six Droughtmaster x Limousin (*Bos taurus*) steers (7.5 head ha^{-1}) for 22 days from 1-23 Apr 1998 (132 animal grazing days). The soil surface was dry when grazing commenced but 125 mm of rain fell on 14-16 Apr, so the cattle were on saturated surface soil for the final 8 days of grazing. After grazing, both bays were sprayed with glyphosate (735 g ha^{-1}) + 2, 4-D (338 g ha^{-1}) on 18 May 1998 in preparation for wheat sowing. Wheat (cv. Hartog) was sown with a zero-till planter in 275 mm rows on 30 May 1998 at a seeding rate of 43 kg ha^{-1} and harvested on 15 Oct 1998. In-crop rainfall was 298 mm. Sorghum (cv. Legend MR) sown on 3 Nov 1998 and harvested on 22 Feb 1999 was used to assess any further residual effects of the 1998 grazing on crop performance.

Measurements: The chronological sequence of all measurements taken in the two trials is shown in Table 1.

Particle Size Analysis (PSA) of soil from the two bays was carried out prior to any experimental treatments. Samples from five selected depth increments 0-0.1, 0.1-0.2, 0.2-0.3, 0.5-0.6 and 0.8-0.9 m were analysed for fractions of coarse sand, fine sand, silt and clay.

Table 1: Chronological sequence of measurements taken

Time of measurement	Measurements (in both bays)
Pre-experimentation	SSS, CI, Ks, PSA
Post-grazing (trial 1)	SSS, CI, Ks, BD, Pw, groundcover %, drawbar force
	Following wheat crop: Establishment, OD weight at anthesis, grain yield
Pre-grazing (trial 2)	OD weight of sorghum stubble
Post-grazing (trial 2)	SSS, CI, Ks, BD, Pw, groundcover %, drawbar force, OD weight of stubble, depth of hoofprints in grazed bay, plastic limit of surface soil
	Following wheat crop: Establishment, OD weight at anthesis, grain yield, weight per grain, no. of grains m^{-2}
	Following sorghum crop: Establishment, OD weight at anthesis, grain yield

SSS = Soil Shear Strength; CI = Cone Index; PSA = Particle Size Analysis; Ks = Saturated hydraulic conductivity; BD = Bulk Density; Pw = Gravimetric soil water content; OD = Oven-Dry

The following soil physical properties were measured in both bays in Nov 1995 (prior to any experimental treatments), May 1996 (after grazing in trial 1) and May 1998 (after grazing in trial 2):

- Soil Shear Strength (SSS) using a 19 mm shear vane by taking 10 measurements at each of two depth increments (0-30 and 70-100) mm at six sites per bay. After trial 2, measurements were taken within and outside the hoof print indentations
- Cone Index (CI) using a recording cone penetrometer fitted with a standard 30˚ included angle 12.83 mm diameter cone[2] by taking three probes at six sites per bay. Readings were recorded every 15 mm from 0-450 mm depth. After trial 2, measurements were taken within and outside the hoof print indentations. Bengough and Mullins[4] concluded that penetrometers provide the best estimates of resistance to root growth in soil, short of direct measurement of root force
- Saturated hydraulic conductivity (Ks) estimated from measurements of unsaturated hydraulic conductivity using disc permeameters at four supply tensions (-10, -20, -30 and -40 mm of water)[15]. Measurements were taken at three sites per bay at both the soil surface and a depth of 100 mm. After trial 2, hydraulic conductivity was measured at the 100 mm depth only, because hoof marks had made the surface microtopography too uneven for surface measurements

The following measurements were taken immediately after grazing in both bays in both trials:

- Bulk Density (BD) and gravimetric soil water content (Pw) at 3 sites per bay using 92 mm diameter undisturbed cores cut into 50 mm increments from 0-200 mm and 100 mm increments from 200-600 mm. In trial 2, bulk density was measured only in the hoof prints to ensure the sampled soil had always been trampled
- Percentage ground cover from a vertical projection by visual estimation of a 1 m^2 quadrat at 6 sites per bay on 2 Apr 1996 and 14 May 1998
- Tractor drawbar force using a dynamometer to pull a direct drill planter at constant speed (5 km h^{-1}) and constant sowing depth (70 mm) on 22 May 1996 (39 readings per bay) and 30 May 1998 (130 readings per bay)
- Establishment of a following wheat crop, by counting plants in 6 m of row at 6 sites per bay on 13 Jun 1996 (21 days) and 12 Jun 1998 (13 days)
- Weight of oven-dry wheat plant tops from 6x1 m^2 quadrats per bay on 28 Aug 1996 (97 days-anthesis), 1 Jul 1998 (32 days) and 18 Aug 1998 (80 days: Anthesis)
- Wheat grain yield (at 12% moisture content) at 6 sites per bay using a small plot header to harvest areas of 33 m^2 on 31 Oct 1996 and 39.6 m^2 on 15 Oct 1998

The following additional measurements were taken in trial 2:

- Weight of oven-dry surface stubble in 6x1 m^2 quadrats per bay on 26 Mar 1998 (pre-grazing) and 14 May 1998 (post-grazing)
- Depth of hoof prints in the grazed bay by placing a straight edge across a hoof print and measuring the depth of the imprint at 18 locations in the bay
- Weight per grain of the following wheat crop using 200-grain samples from 6 sites per bay; and the number of wheat grains m^{-2} calculated by dividing grain yield by weight per grain
- Gravimetric soil water content (Pw) (0-1200 mm in 100 mm increments) in the post-grazing wheat crop at sowing and harvest using 25.4 mm diameter cores at three sites per bay. These data enabled calculation of soil water use to a depth of 1200 mm and crop Water Use Efficiency (WUE) defined as grain yield/(soil water use + in-crop rainfall)
- Plastic limit of the surface soil at 0-100 mm in each bay. Two composite samples from 20 randomly selected sites were taken in each bay and plastic limits were determined as described in the Australian Standard AS 1289.3.2.1[3]

The following measurements were taken in the second crop (sorghum) following the 1998 grazing to find any further residual effects on soil properties and crop performance:

- Sorghum establishment by counting plants in 20 m of row at 6 sites per bay on 4 Dec 1998
- Weight of oven-dry plant tops from 6x1 m^2 quadrats per bay on 14 Jan 1999 (72 days: anthesis)
- Grain yield (at 12% moisture content) using a small plot header to harvest areas of 36 m^2 at six sites per bay on 22 Feb 1999

Statistical analysis: Pre-trial measurements of grain yield and crop establishment were available from 4 wheat and 2 sorghum crops grown in the two contour bays selected. Analysis of variance was used to compare bay performance for wheat and sorghum (separately), with each crop grown treated as a replicate. Because the subsequent treatment (grazing) effects would be confounded with any inherent differences between the bays, such pre-trial data aids interpretation by quantifying such differences. Where replicated samples were taken within the bays after grazing, t-tests were used to compare bay performance.

RESULTS

Pre-trial data: No differences between the bays in soil physical properties, crop establishment or grain yield were evident prior to the commencement of any grazing treatments (Table 2). These results indicate there were no major differences between the bays, so any differences observed after the trials can be attributed to the effects of grazing.

Ground cover: Immediately after grazing in trial 1, there was no difference in percentage ground cover between the bays (Table 3). In trial 2, the grazing cattle did not remove all the stubble. The mean weight of oven-dry sorghum stubble declined by 315 kg ha^{-1} in the ungrazed bay and by 1287 kg ha^{-1} in the grazed bay during the 49-day period from 26 Mar-14 May (Table 3). This indicates the cattle removed 972 kg ha^{-1} of dry matter, yet grazing caused no immediate decline in percentage ground cover immediately after grazing (Table 3).

Surface topography: In trial 1, hoof prints were barely evident on the dry surface soil after grazing, indicating minimal impact of the cattle on the properties of the surface soil. In trial 2, however, the mean depth of hoof imprints as a result of grazing during and immediately after rain was 49 mm.

Table 2: Pre-trial comparison of the control and grazed bays (the soil measurements were taken in November 1995)

Measurement	Control	Grazed	Significance level
SSS (kPa): 0-30 mm	5.2	5.8	ns
70-100 mm	59.1	68.6	ns
CI (MPa): 0.06 m	0.79	0.89	ns
0.12 m	1.72	1.85	ns
0.18 m	1.93	2.05	ns
0.24 m	1.80	2.12	ns
0.30 m	1.84	2.06	ns
0.36 m	1.82	1.96	ns
Ks (mm h^{-1}): 0.mm	453	710	ns
100 mm	314	524	ns
Pw, 0-0.6 m (mm):	176	166	ns
Clay/Silt/Sand (%):			
0.0-0.1 m	36/9/55	33/12/57	Statistical
0.1-0.2 m	40/9/51	39/10/52	analysis
0.2-0.3 m	43/9/48	39/10/52	not possible
0.5-0.6 m	42/9/49	37/8/56	
0.8-0.9 m	43/10/48	36/9/56	
Wheat establishment (%)	56	48	ns
Wheat grain yield (kg ha^{-1})	2927	3338	ns

SSS = Soil Shear Strength; CI = Cone Index; Ks = Saturated hydraulic conductivity; BD = Bulk Density; Pw = Gravimetric soil water content; OD = Oven-Dry; ns = not significant ($p>0.10$)

Soil physical properties: After grazing in trial 1, there were no differences between the control and grazed bays in any of the soil physical properties measured i.e. SSS, CI, Ks, BD and Pw (Table 3). This grazing commenced 35 days after rain when Pw was below the plastic limit at 0-50 and 50-100 mm in both bays (data not shown). The plastic limit of the surface soil was 17.0% in the grazed bay and 17.5% in the control bay. With negligible rainfall during grazing in trial 1, the soil water content remained below the plastic limit in the top 100 mm of soil throughout the grazing period.

Since there were no effects of grazing on soil physical properties in trial 1, there were also no effects that could be carried over into trial 2 two years later. Yet after grazing in trial 2, there were significant differences in soil physical properties between the bays. SSS at both 0-30 and 70-100 mm was significantly higher in the grazed bay than the control bay (Table 3). Soil CI in the grazed bay was significantly higher than in the ungrazed bay at most depths between 100 and 450 mm (Fig. 1A). When depths were adjusted for the depth of the hoof prints (49 mm), however, CI generally showed no significant differences between the bays (Fig. 1B). Drawbar force required to pull the direct drill planter was twice as much in the grazed bay as the control bay (Table 3). Since planting speed was constant, the drawbar power (force x speed) that was required also doubled. There were no differences ($p>0.05$), however, in BD, Ks or Pw after the subsequent fallow (Table 3).

Table 3: Effect of grazing on soil physical properties and the following wheat and sorghum crops

	Trial 1			Trial 2		
Measurement	Control	Grazed	Significance level	Control	Grazed	Significance level
Ground cover (%)	75	75	ns	33	38	ns
Weight OD stubble (kg ha^{-1}):						
Pre-grazing	-	-	-	2907	2966	ns
Post-grazing	-	-	-	2592	1679	0.005
Ks (mm h^{-1}):						
0 mm	638	1019	ns	-	-	-
100 mm	126	613	ns	420	45	ns
Drawbar force (kN)	1.9	11.2	ns	9.5	19.3	<0.001
SSS (kPa):						
0-30 mm	9.5	9.6	ns	7.0	13.5	<0.05
70-100 mm	37.4	34.6	ns	21.6	27.6	<0.01
BD (Mg m^{-3}):						
0-50 mm	0.92	1.04	ns	0.77	0.85	ns
50-100 mm	1.34	1.36	ns	1.11	1.23	ns
100-150 mm	1.48	1.41	ns	1.31	1.43	0.055
150-200 mm	1.59	1.52	ns	1.44	1.48	ns
200-300 mm	1.61	1.62	ns	1.51	1.51	ns
300-400 mm	1.68	1.69	ns	1.56	1.62	ns
400-500 mm	1.73	1.70	ns	1.60	1.55	ns
500-600 mm	1.76	1.78	ns	1.60	1.60	ns
Pw at wheat sowing (mm):						
0-600 mm	177	189	ns	207	204	ns
0-1200 mm	-	-	-	366	340	ns
Pw at wheat harvest (mm):						
0-1200 mm	-	-	-	3370	307	ns
Net soil water use (mm):						
0-1200 mm	-	-	-	29	33	ns
Wheat establishment (%)	58	51	ns	58	52	ns
OD wheat tops (kg ha^{-1}):						
32 days	-	-	-	108	720	<0.05
Anthesis	2451	2711	Unreplicated	2149	2241	ns
Wheat grain yield (kg ha^{-1})	1072	1167	Unreplicated	1666	1408	0.009
Weight/wheat grain (mg)	35.2	33.9	Unreplicated	45.9	44.4	0.023
No. of wheat grains m^{-2}	3045	3443	Unreplicated	3631	3174	0.038
Wheat WUE (kg ha^{-1}.mm)	-	-	-	5.1	4.2	0.003
Sorghum establishment (%)	-	-	-	49	44	ns
OD sorghum tops (kg ha^{-1}):						
Anthesis	-	-	-	2193	2121	ns
Sorghum grain yield (kg ha^{-1})	-	-	-	526	983	0.006

SSS =Soil Shear Strength; Ks = Saturated hydraulic conductivity; BD = Bulk Density; Pw = Gravimetric soil water content; OD = Oven-Dry; WUE = Water Use Efficiency; ns = not significant (p>0.10)

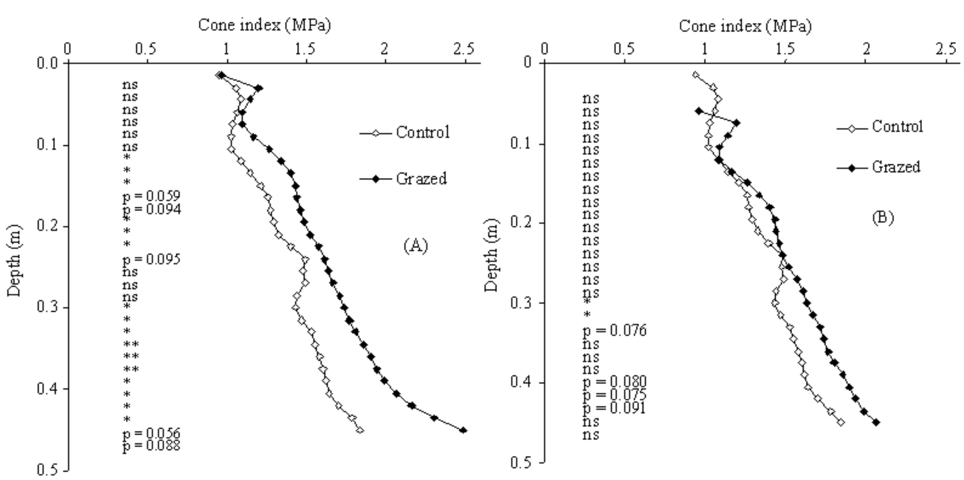

Fig. 1: Effect of grazing in 1998 on cone index (MPa) from 0 to 0.45 m (all measurements shown were taken in hoof print indentations). (A): Comparison based on depth below soil surface. (B): Comparison based on depth below original soil surface (using the mean depth of the hoof prints). ◊: Control; ♦: Grazed

Establishment of the following crop: Prior to any grazing, there were no differences (p>0.05) between the two bays in the establishment of two sorghum crops or four wheat crops. The establishment of wheat two months after grazing in trial 1 and 37 days after grazing in trial 2 was again not different (p>0.05) between the bays. These data indicate that in both trials, when a zero-till planter was used, the grazing treatment did not affect subsequent crop establishment.

Biomass of the following crop: Wheat dry matter at anthesis showed no decline in the grazed bay in either trial. After grazing in trial 2, however, the early growth of the wheat was affected: the dry weight of the plant tops was reduced 32 days after sowing (Table 3).

Grain yield of the following crop: Before any grazing was imposed, there were no differences between the two bays in their yield of wheat or sorghum. The wheat yield following trial 1 also did not differ (p>0.05) between the control and grazed bays (Table 3). Yield of the wheat crop following trial 2, however, was lower (p<0.01) in the grazed bay than the control bay. The 16% yield reduction was a result of reductions (p<0.05) in both weight per grain by 13% and grain number per unit area by 3% (Table 3).

WUE of the following crop: After trial 2, the WUE of the following wheat crop was lower (p<0.01) in the grazed bay than the control bay (Table 3). Levels of WUE were low in both bays (Table 3) because high in-crop rainfall (298 mm) resulted in runoff and water logging during crop growth.

Second crop after grazing in trial 2: The second crop after trial 2 (sorghum in 1998/99) produced similar (p>0.05) quantities of dry matter in both bays but yielded more (p<0.01) grain in the grazed than the control bay (Table 3). This means there was no evidence of negative carryover effects on yield in the second crop after grazing.

DISCUSSION

The pertinent issue is whether grazing of crop stubble by cattle can be profitably incorporated into a sustainable farming system. Does stubble grazing compromise surface cover and soil condition and therefore adversely affect subsequent crop performance? If so, do the adverse effects outweigh the benefits derived from grazing? Proffitt *et al*.[18] have shown that the soil water content when a soil is trampled is a major determinant of the severity of soil compaction.

Stubble grazing caused no immediate decline in ground cover in either of the two trials. Re-orientation of the stubble in the grazed bay had changed from mostly erect to mostly prostrate due to trampling, resulting in no change in ground cover despite a reduced weight of plant residues (Table 3). So although about 1 t ha^{-1} of residues had been removed, the remaining residues provided levels of surface cover similar to those in the control bay. This means there was no reduction in soil surface protection immediately after grazing. In both trials, the level of cover after grazing exceeded 20-30%, which reduces soil erosion dramatically[6]. In the longer term, however, residues in contact with the soil as a result of trampling may decompose more rapidly and result in reduced cover.

Stubble grazing increased surface roughness when the surface soil was saturated (trial 2). The depressions left by the cattle hooves were observed to retain rain water which might otherwise have run off because the surface soil was compacted. There were no treatment differences in soil water content after grazing in trial 2 (Table 3).

Stubble grazing increased compaction in the surface soil when it was saturated (trial 2) but not when it was dry (trial 1). Animal trampling at times when the surface soil obviously exceeded its plastic limit increased SSS at 0-30 and 70-100 mm compared with the ungrazed control (Table 3). Proffitt *et al*.[16,18] reported similar findings under a traditional sheep grazing system, in which grazing increased soil strength and bulk density and McDowell *et al*.[12] obtained similar results under grazed dairy pastures. The drawbar power required to pull a direct drill planter set at a depth of 70 mm was higher in the grazed treatment than the control (Table 3). At a depth of 100 mm, however, no difference in Ks was detected (Table 3). Although CI showed increases below 100 mm after grazing in trial 2, adjustment for the depth of the hoof prints indicated the increases were artefacts of the depth of sampling (Fig. 1). Some degree of compaction, however, was already present in both bays; Hazelton and Murphy[9] indicate that cereal root growth is greatly restricted at penetrometer resistances of 1.25-2.00 MPa and values recorded in this study lay within, or exceeded, this range below 150 mm.

Stubble grazing did not significantly affect the establishment of a subsequent wheat crop after trials 1 and 2, a result we attribute to the use of a state-of-the-art zero-till planter at the optimum time for sowing. The planter incorporated a robust frame, tines with high breakout force, smooth coulters, narrow sowing points and suitably weighted press wheels. High-breakout tines ensure a uniform depth of seed placement in compacted soil. If conventional combine planting machinery had been used, grazing would have reduced crop establishment markedly because the spring-loaded tines of combine planters penetrate only finely tilled seedbeds. Proffitt *et al*.[17] found that a tillage operation was required prior to planting after traditional grazing but that direct drilling was also possible. Since we found no effect on establishment, any reductions in the depth of soil above the seed at the sites of the hoof print depressions were not important. The increased drawbar power required by the zero-till planter in 1998 indicates greater energy expenditure for crop establishment, which was apparently due to the soil compaction after grazing on saturated soil. It is noteworthy that crop establishment was not reduced when the zero-till planter described above was used after applying a 10 Mg axle load to a Vertisol while it exceeded its plastic limit[19].

Wheat grain yield was reduced after stubble grazing in trial 2 but not trial 1. Proffitt *et al*.[17] found that grazing did not affect the yield of a subsequent wheat crop but did reduce grain protein content. WUE of the wheat grown after trial 2 was also slightly reduced in the grazed bay compared with the control (Table 3). We suggest that the compacted surface soil following grazing in trial 2 reduced rainfall infiltration or early root growth or both, thereby reducing yield and WUE. Restricted early root growth is indicated by the reduced dry matter production at 32 days compared with the control bay (Table 3). Also, yield reduction was due largely to a reduced number of grains per unit area (Table 3) and grain number is a yield component determined prior to anthesis.

In trial 1, grazing on dry soil had no adverse effect on soil physical properties, crop establishment or grain yield and caused no reduction in protective ground cover in the short term. This result indicates that under a similar regime of very dry soil and no rainfall during grazing, no adverse effects of stubble grazing are likely. It follows that if grazing can be restricted to times when the surface soil is dry enough to cause minimal compaction by animals, there is little risk of adverse effects on subsequent crop performance. This can be achieved by introducing stock only when the surface soil is below its plastic limit to a depth of at least 50 mm and removing them before rain rewets the soil. Although trampling on dry soil decreased soil macroporosity and aggregate size on a Typic Natraquoll, the damaged soil pores regenerated and aggregate stability recovered during subsequent wetting and soil swelling[22].

In trial 2, grazing over an eight-day period on saturated soil increased SSS and drawbar power requirement and reduced the yield of the next crop. During that time, only 60% of the bay area was covered by animal hooves, assuming each animal covered 0.01 ha day^{-1}[5]. These results indicate a potential risk in grazing stubble when the surface soil is susceptible to compaction by animal hooves i.e. when soil at or near the surface has a water content exceeding the plastic limit. Increased soil water content reduces soil strength, which increases the soil's susceptibility to compaction[18].

Stubble grazing is recommended only while the surface soil remains dry enough to minimise soil compaction by the hooves of grazing animals. The challenge for growers is to time the grazing period to avoid periods of rainfall. Therefore controlled grazing (instead of set stocking) is required. This means growers must be able to move animals to a suitable alternative area at short notice when rainfall is imminent. The difficulty in achieving this may dictate whether or not stubbles are regularly grazed. Key factors for individual enterprises are the priority placed on other farm operations and the accuracy and effective use of short-range weather forecasting.

Our trials were atypical compared with current stubble grazing practice in central Queensland. We used high stocking rates for short periods (12.5 head ha^{-1} for 15 days and 7.5 head ha^{-1} for 22 days), or crash grazing, but common practice is to use lower rates for longer periods. Typically 1.5-2.5 head ha^{-1} are grazed for 60-120 days, during which time rain is likely to fall (K. McCosker, pers. comm.). If grazing is necessary during a drought, however, a set stocking approach is likely to be used to maximise the grazing period. Should a decision be made to graze long-term, the grazing value must be weighed against the potential yield loss from the subsequent crop. Soil is likely to be compacted and ground cover is liable to fall below 30%.

It has also been argued that our results lack relevance because they were obtained on a degraded soil (with high cone indices and no fertiliser applied after 13 and 15 years of cropping). However, the site closely matches the soil condition of large tracts of cropping land in the central Queensland region.

The timing of stubble grazing should be considered. If grazing is delayed after a sorghum harvest, for example, the harvested crop may continue to use soil water. Ideally, grazing of sorghum stubble should commence as soon as possible after the harvest. This is also an appropriate time because the entire soil profile is typically dry after a sorghum harvest, particularly during a drought when the need for stubble grazing is most urgent. Also, since sorghum in central Queensland is usually harvested in late autumn, the period immediately after harvest occurs during winter when rainfall is low, rogue storms are less likely and rainfall events are more predictable than in summer.

Even when grazing on dry surface soil is possible, further issues may arise. The value of the feed resource must be weighed against the value of the stubble in increasing rainfall infiltration and reducing soil erosion on sloping land. On the other hand, removal of an excessive stubble load may facilitate sowing operations. Stubble grazing may also be useful in suppressing weeds. In trial 1, stubble grazing controlled sorghum regrowth, whereas there was abundant regrowth in the control bay that needed spraying. A distinction should be made between dead sorghum stubble, which has been sprayed out and green stubble such as we used. Green stubble provides higher-quality animal feed than dead stubble but also uses soil water before and during grazing. For optimum productivity from the cropping enterprise, sorghum should be sprayed out at physiological maturity, which is indicated by a black layer on the seed[7].

To some dedicated grain growers, stubble grazing will always remain an anathema on their pristine cropping soils because they regard any soil compaction as undesirable. However, to remain profitable, managers of farming systems involving both grain and cattle production will always need to be more flexible. For these enterprises, grim reality dictates that compromise will be necessary during an extreme drought when crop stubbles such as sorghum can provide valuable feed for livestock.

CONCLUSION

Grazing did not reduce soil surface cover in the short term, so immediate protection by crop residues against rainfall impact, runoff and erosion was maintained; nor did grazing reduce the establishment of subsequent wheat crops when a direct drill planter was used. On the extremely dry soil in trial 1, stubble grazing caused no adverse changes in soil physical properties or crop performance post-grazing. In trial 2, however, grazing during and after rain resulted in increased SSS, required greater tractor power at sowing and reduced the yield of a subsequent crop. Stubble grazing is therefore not recommended when there is a risk of soil compaction by animal hooves but is a useful option in mixed farming enterprises when dry surface soil minimises the risk of compaction. Further research is needed to quantify this risk under different soil, environment and management conditions.

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REFERENCES

1. Alderfer, R.B. and R.R. Robinson, 1947. Runoff from pastures in relation to grazing intensity and soil compaction. J. Am. Soc. Agron., 39: 948-958. http://agron.scijournals.org/content/vol39/issue11/.
2. ASAE Standard S313.3, 2004. American Society of Agricultural and Biological Engineers. Niles Road, St. Joseph, Michigan, USA.
3. Australian Standard AS 1289.3.2.1, 1995. Methods of testing soils for engineering purposes-soil classification tests-Determination of the plastic limit of a soil-standard method. http://webstore.ansi.org/FindStandards.aspx?SearchString=1289.3.2.1&SearchOption=0&PageNum=0&SearchTermsArray=null%7c1289.3.2.1%7cnull.
4. Bengough, A.G. and C.E. Mullins, 1990. Mechanical impedance to root growth: A review of experimental techniques and root growth responses. J. Soil Sci., 41: 341-358. DOI: 10.1111/j.1365-2389.1990.tb00070.x
5. Farris, E.J., 1954. Activity of dairy cows during estrus. J. Am. Vet. Med. Assoc., 125: 117-120. http://www.ncbi.nlm.nih.gov/pubmed/13183851.
6. Freebairn, D.M. and G.H. Wockner, 1986. A study of soil erosion on vertisols on the eastern Darling Downs, Queensland. I. Effects of surface conditions on soil movement within contour bay catchments. Aust. J. Soil Res., 24: 135-158. DOI: 10.1071/SR9860135.
7. Giles, K.L., H.C.M. Bassett and J.D. Eastin, 1975. The structure and ontogeny of the hilum region in *Sorghum bicolor*. Aust. J. Bot., 23: 795-802. http://www.publish.csiro.au/?act=view_file&file_id=BT9750795.pdf

8. Greenwood, K.L. and B.M. McKenzie, 2001. Grazing effects on soil physical properties and the consequences for pastures: a review. Aust. J. Exp. Agric., 41: 1231-1250. http://www.publish.csiro.au/?act=view_file&file_id=EA00102.pdf
9. Hazelton, P. and B. Murphy, 2007. Interpreting Soil Test Results: What do all the Numbers mean? 2nd Edn., CSIRO Publishing, Collingwood, Victoria, Australia, ISBN: 9780643092259, p: 23.
10. Isbell, R.F., 1996. The Australian Soil Classification. 1st Edn., CSIRO Publishing, Collingwood, Victoria, Australia, ISBN: 0-643-05813-3, p: 143.
11. Linnartz, N.E., C. Hse and V.L. Duvall, 1966. Grazing impairs physical properties of a forest soil in Central Louisiana. J. Fore., 64: 239-243. http://www.ingentaconnect.com/content/saf/jof/1966/00000064/00000004/art00006;jsessionid=14khobg4mm2fe.alexandra?format=print.
12. McDowell, R.W., J.J. Drewry, R.W. Muirhead and R.J. Paton, 2005. Restricting the grazing time of cattle to decrease phosphorus, sediment and E. coli losses in overland flow from cropland. Aust. J. Soil Res.,43:61-66. http://cat.inist.fr/?aModele=afficheN&cpsidt=16568486.
13. Orr, H.K., 1975. Recovery from soil compaction on bluegrass range in the Black Hills. Trans. Am. Soc. Agric. Eng., 18: 1076-1081. http://md1.csa.com/partners/viewrecord.php?requester=gs&collection=ENV&recid=7606362&q=&uid=&setcookie=yes.
14. Packer, I.J., 1988. The Effects of Grazing on Soils and Productivity: A Review. Soil Conservation Service of NSW Technical Report No. 4, ISSN: 1031-8321, p: 3.
15. Perroux, K.M. and I. White, 1988. Designs for disc permeameters. Soil Sci. Soc. Am. J., 52: 1205-1215. http://soil.scijournals.org/cgi/content/abstract/52/5/1205.
16. Proffitt, A.P.B., S. Bendotti and D. McGarry, 1995. A comparison between continuous and controlled grazing on a red duplex soil. I. Effects on soil physical characteristics. Soil Tillage Res., 35: 199-210. DOI: 10.1016/0167-1987(95)00486-6.
17. Proffitt, A.P.B., S. Bendotti and G.P. Reithmuller, 1995. A comparison between continuous and controlled grazing on a red duplex soil. II. Subsequent effects on seedbed conditions, crop establishment and growth. Soil Tillage Res., 35: 211-225. DOI: 10.1016/0167-1987(95)00487-4.
18. Proffitt, A.P.B., R.J. Jarvis and S. Bendotti, 1995. The impact of sheep trampling and stocking rate on the physical properties of a red duplex soil with two initially different structures. Aust. J. Agric. Res., 46: 733-747. DOI: 10.1071/AR9950733.
19. Radford, B.J., D.F. Yule, D. McGarry and C. Playford, 2007. Amelioration of soil compaction can take 5 years on a Vertisol under no till in the semi-arid subtropics. Soil Tillage Res., 97: 249-255. DOI: 10.1016/j.still.2006.01.005.
20. Rhoades, E.D., L.F. Locke, H.M. Taylor and E.H. McIlvain, 1964. Water intake on a sandy range as affected by 20 years of differential cattle stocking rates. J. Range Manage., 17: 185-190. http://digitalcommons.library.arizona.edu/holdings/journal/issue?r=http://jrm.library.arizona.edu/Volume17/Number4/
21. Stephenson, G.R. and A. Veigel, 1987. Recovery of compacted soil on pastures used for winter cattle feeding. J. Range Manage., 40: 46-48. http://www.fao.org/agris/search/display.do?f=./1987/v1315/US8730895.xml;US8730895.
22. Taboada, M.A. and R.S. Lavado, 1993. Influence of cattle trampling on soil porosity under alternate dry and ponded conditions. Soil Use Manage., 9: 139-143. DOI:10.1111/j.1475-2743.1993.tb00943.x.
23. Willatt, S.T. and D.M. Pullar, 1983. Changes in soil physical properties under grazed pastures. Aust. J. Soil Res., 22: 343-348. DOI: 10.1071/SR9840343.