Field Crops Research 196 (2016) 22–32

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Sheep grazing on crop residues do not reduce crop yields in no-till, controlled traffic farming systems in an equi-seasonal rainfall environment

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ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form 26 May 2016
Accepted 30 May 2016
Available online 18 July 2016

Keywords:
Water
Nitrogen
Compaction
Soil
Stubble

ABSTRACT

In southern Australia, the majority of farms combine a sheep enterprise with a cropping enterprise to form a mixed farming business. Crops are grown in sequence with pastures, and sheep graze vegetative juvenile crops and crop stubble residues after harvest. Recently, growers practicing no-till, controlled traffic cropping became concerned that grazing livestock would damage soil and reduce soil water capture, crop yield and profitability. Sheep grazing on stubbles remove residue cover and compact surface soil, but there is little published research on potential impacts on subsequent crop performance.

Two experiments were conducted in high (Temora) and low (Condobolin) rainfall environments from 2009 to 2013 to determine whether sheep grazing crops during the vegetative phase and/or stubbles after harvest damaged soil, reduced soil water capture and storage or affected the performance of subsequent crops. Sheep grazing on stubbles did not reduce crop yields provided summer weeds were controlled with herbicides and at least 70% stubble cover (2–3 t/ha cereal stubble) was maintained on the soil surface. Sheep grazing on stubble increased soil strength and bulk density and reduced water infiltration rates, but rarely to levels that were detrimental to soil water capture, crop growth or grain yield. Where reduced infiltration rates did reduce soil water capture, it was due to removal of cover by grazing rather than compaction.

Grazing of vegetative crops in winter when soils were generally wet further increased soil strength compared to grazing stubbles alone, but not to an extent that was detrimental to plant growth. Yield effects from grazing crops in winter were not due to soil physical effects, but to differences in plant growth in response to defoliation.

Grazing of both stubbles and crops increased the availability of soil mineral N to subsequent crops which increased grain yield and protein in some seasons.

The results from these experiments provide strong evidence that livestock can be retained within modern conservation cropping systems without compromising crop performance, and continue to provide the production and business risk benefits for which they have been historically valued.

1. Introduction

A livestock enterprise, particularly sheep (*Ovis aries*), in conjunction with a wheat-based (*Triticum aestivum*) cropping enterprise has long formed the basis of mixed farming systems in southern Australia (Bell and Moore, 2012; Kirkegaard et al., 2011). In southern NSW (SNSW) where livestock often comprise 50% of farm enterprise by area, rainfall is equi-seasonal, but crops are grown only during the cool half of the year from April to December. During the warm summer months, cropping land is left fallow and sheep

Abbreviations: NG, nil graze; SG, stubble graze; WSG, winter and stubble graze; MG, moderate graze; HG, heavy graze; SB, stubble burn; SR, stubble retain; SM, stubble mown and removed; SA, additional stubble added; SRW, stubble retained & summer weeds not controlled.

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http://dx.doi.org/10.1016/j.fcr.2016.05.012
0378-4290/

graze stubble residues and weeds that germinate in response to summer rain (Hunt et al., 2009). Recent research has re-evaluated the contribution that summer fallow rain makes to winter crop yield (Hunt and Kirkegaard, 2011) versus grazing value of summer weeds (Moore and Hunt, 2012) and weeds growing on fallows are now predominantly controlled with herbicide to allow accumulation of soil water and mineral nitrogen (N) for use by subsequent crops (Hunt et al., 2013; Kirkegaard et al., 2014). However, crop residues are still a highly valuable feed source and stock are grazed on them in situ following chemical control of summer fallow weeds. This is somewhat different to other regions of the world where sheep are grazed on fallows specifically to control fallow weeds (e.g. Barsotti et al., 2013; Hatfield et al., 2007; Lenssen et al., 2013; Sainju et al., 2014).

The mix of a livestock and cropping enterprise in this environment is fundamentally symbiotic, as the sheep consume and give value to by-products from the cropping enterprise (e.g. crop stubbles following harvest, weather damaged and spilt grain, Thomas et al., 2010) and early vegetative crop growth (Dove and Kirkegaard, 2014). Legume-based pasture phases used for sheep production allow fields to be spelled from crop production, increase soil N fertility and reduce levels of crop weeds and diseases (Peoples et al., 1998). The presence of both livestock and crops also diversifies farm business, offsetting production and price risk and increasing resilience (Bell and Moore, 2012; Fisher et al., 2012).

In recent times much credence has been given to the potential for conservation farming practices such as no-till seeding with complete residue retention and controlled traffic to increase crop productivity in the face of rising global food demand and declining resources (Derpsch et al., 2010). Adoption of no-till has been rapid in SNSW and now comprises the majority of cropped land in the region (Llewellyn et al., 2012). Adoption of controlled traffic has been less extensive due to higher investment costs and less demonstrated benefit (Anon., 2009).

Following recent declines in growing season rainfall (Cai et al., 2012; Verdon-Kidd and Kiem, 2009), many growers in SNSW, especially those practicing no-till cropping, became concerned that grazing livestock were reducing soil water capture and storage during the summer fallow period, and consequently crop yield and profitability. Some proponents argued that the full potential of conservation farming systems may not be realised if sheep are grazed on cropping country, removing residue cover (Govaerts et al., 2009) and compacting soils (Hamza and Anderson, 2005).

Bell et al. (2011) reviewed studies investigating effects of grazing on soil properties and subsequent crop performance. They concluded that whilst treading by livestock increases soil strength and bulk density and reduces macro-porosity and infiltration rate, the effects are shallow (0–0.1 m) and transient due to amelioration through natural processes or tillage. Only two of seven published studies investigating grazing effects on crop yield found a negative response to grazing, and both of these were by cattle grazing on wet, unfrozen soil (Clark et al., 2004; Radford et al., 2008). Bell et al. (2011) also report two field experiments in SNSW which found no effect of sheep grazing on subsequent crop growth or yield, despite evidence of surface compaction and reduced infiltration rate.

More recently, Allan et al. (2016) report a study comprising 31 site years conducted in the Mediterranean-type environments of southern Australia and found that summer grazing of crop residues had little impact on amount of residue, soil properties, soil water storage, weeds and yield of the following crops. However, these experiments were conducted in environments with little summer rainfall, and at relatively low grazing intensities (15–1420 sheep/ha days). Equi-seasonal rainfall in SNSW increases chances of grazing occurring on wet soil which is likely to be more damaging (Bell et al., 2011; Radford et al., 2008). Stocking rates are also higher in SNSW compared to most of the locations used in the study of Allan et al. (2016), which they felt was an important factor in explaining the one site year in which they observed a negative yield response (956 sheep/ha days).

Mixed farming necessitates some compromise between optimal management of the crop enterprise, and optimal management of the livestock enterprise. Fisher et al. (2012) argued that greater understanding of possible trade-offs between livestock production and no-till systems is required in order to better integrate animal and cropping enterprises. This study aimed to quantify trade-offs between livestock grazing and crop production due to changes in soil physical properties and crop resource capture and use, in particular soil water and N. Two field experiments were designed to determine the impact of sheep grazing on soil properties and crop growth under no-till, controlled traffic cropping with strict weed control. The sheep grazed on crop residues (summer) and crops during the vegetative phase (winter). In maintaining contemporary practice of strict summer weed control, the study differs from others which have focussed on the role of sheep in controlling summer fallow weeds (Barsotti et al., 2013; Hatfield et al., 2007; Lenssen et al., 2013; Sainju et al., 2014), or have allowed weeds to remain as a treatment effect on subsequent crop production (Allan et al., 2016).

2. Methods

2.1. Experiment 1—Temora

2.1.1. Site description

Experiment 1 was located on a red chromosol soil (Isbell, 2002) with little slope 5 km SSE of the township of Temora in SNSW (S 34.49°, E 147.51°, 299 m ASL) which has a mean (1963–2013) annual rainfall of 520 mm, 313 mm of which fall during the wheat growing season from April-October. A tipping bucket rain-gauge at the site recorded daily rainfall.

Crop lower limit (CLL), drained upper limit (DLL), bulk density and various soil physical and chemical properties (Table 1) were measured at three locations across the site as per the methods of Burk and Dalgliesh (2008). These characterisation areas were also used to generate calibration curves for a neutron moisture meter (CPN International, Martinez, CA) which was used to measure soil water in the experiment.

2.1.2. Treatments and experimental design

The experiment at Temora consisted of three grazing treatments (nil graze—NG, stubble graze—SG, winter and stubble graze—WSG) applied in a factorial randomised complete block design with two stubble management treatments (stubble burn—SB, stubble retain—SR) and four replicates. Treatments were applied in two different phases in adjoining areas of a farmer's paddock which had been in lucerne (*Medicago sativa*) pasture since 2005. In Phase 1, lucerne was terminated with herbicide in late spring 2008, in Phase 2 it was terminated in late winter 2009. Following lucerne removal, large plots (7.25 × 16.00 m) were established which allowed all operations to be conducted using controlled traffic, which removed machinery compaction as a confounding factor in the experiment. All plots were fenced so they could be individually grazed by sheep.

All crops were inter-row sown using a plot seeder equipped with contemporary no-till seeding equipment. This consisted of six Flexi-Coil 250 kg break-out tines (Flexi-Coil Australia, St Marys, NSW Australia) set on 305 mm row spacing and fitted with Agmaster® boots, 12 mm knife points and press wheels (Agmaster, Welshpool, WA Australia).

Crops were sown in mid-late April in all years of the experiment, and both crop phases were kept in a rotation of canola (*Brassica napus*)-wheat–wheat which is widely practiced in the

Table 1
Soil physical properties to-depth at the experimental site at Temora. All values are means from three characterisation areas from across the experimental site.

Depth (m)	Bulk Density (Mg/m^3)	Soil water content at drained upper limit (m^3/m^3)	Soil water content at wheat lower limit (m^3/m^3)	Soil water content at canola lower limit (m^3/m^3)	Soil water content when air dry (m^3/m^3)	Soil water content at 1500 kPa (m^3/m^3)	Sand (%)	Silt (%)	Clay (%)	pH ($CaCl_2$)
0–0.05	1.35	0.348	0.026	0.038	0.017	0.079	57	27	16	4.7
0.05–0.15	1.54	0.275	0.052	0.069	0.025	0.094	48	30	22	4.9
0.15–0.25	1.66	0.255	0.085	0.113	0.032	0.116	44	28	27	5.3
0.25–0.35	1.66	0.279	0.133	0.179	0.053	0.192	37	23	40	5.3
0.35–0.45	1.65	0.313	0.204	0.215	0.028	0.223	33	21	46	5.6
0.45–0.55	1.67	0.327	0.220	0.213	0.031	0.236	31	22	48	5.6
0.55–0.65	1.70	0.317	0.194	0.192	0.028	0.212	32	25	43	5.9
0.65–0.75	1.72	0.310	0.163	0.196	0.027	0.207	32	26	42	5.9
0.75–0.85	1.63	0.350	0.235	0.247	0.037	0.259	25	20	55	6.0
0.85–0.95	1.64	0.350	0.236	0.246	0.038	0.259	25	21	54	6.0
0.95–1.05	1.66	0.338	0.222	0.232	0.036	0.239	29	23	48	6.3
1.05–1.15	1.65	0.330	0.192	0.214	0.033	0.220	35	22	42	6.3
1.15–1.25	1.60	0.336	0.190	0.223	0.029	0.182	39	24	36	6.5
1.25–1.35	1.58	0.324	0.221	0.187	0.030	0.191	35	26	39	6.5
1.35–1.45	1.62	0.317	0.247	0.189	0.032	0.235	34	24	42	6.5
1.45–1.55	1.65	0.310	0.278	0.209	0.032	0.213	39	19	42	6.5
1.55–1.65	1.67	0.311	0.303	0.229	0.032	0.215	41	18	41	6.6
1.65–1.75	1.68	0.307	0.304	0.254	0.032	0.211	45	16	39	6.6
1.75–1.85	1.68	0.301	0.302	0.277	0.033	0.216	43	16	41	6.6

Table 2
Grazing treatments applied to crop and stubble at the Temora site in Phases 1 and 2.

		Winter graze (crop)		Summer graze (stubble)	
Phase	Year & crop	Date	Grazing intensity (sheep/ha days)	Date	Grazing intensity (sheep/ha days)
1	2009 (wheat)	18–19 June, 7–9 July	517	30 Nov-7 December	2414 on SG treatments, 1810 on WSG treatments
	2010 (canola)	30 June-1 July	517	13–18 December	1724
	2011 (wheat)	23 June	359	6–12 December	2586
	2012 (wheat)	20–21 June	442	–	–
	2013 (canola)				
2	2010 (wheat)	25–26 June	129	13–18 December	3448
	2011 (canola)	25 June	1078	6–12 December	1293
	2012 (wheat)	20–21 June	442	–	–

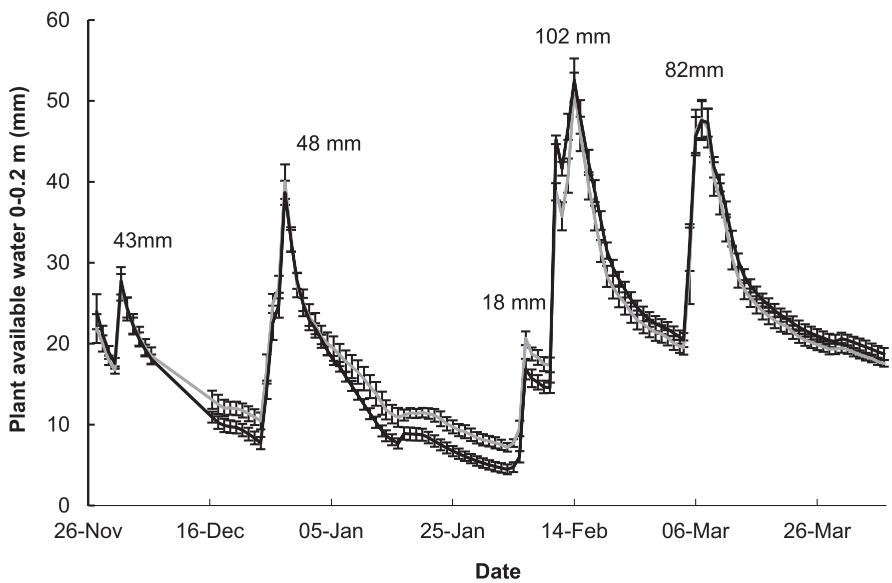

Fig. 1. Plant available water from 0 to 0.2 m depth at 9:00 am each day as measured by TDR probes in the nil graze (▬) and stubble & winter graze treatments (▬) during the summer fallow of 2009/2010 in Phase 1 of the Temora experiment. The numbers next to curve peaks are amounts of rainfall in corresponding events. Error bars are +/− standard error of means and means with overlapping bars are unlikely to be significantly different.

area. All wheat cultivars were of hard white milling quality. Merino ewes (3–8 per plot) were used to graze crops in WSG treatments in winter whilst crops were still in the vegetative stage (Table 2). Following harvest in each year (late November-early December), weaner ewes grazed stubbles in SG and WSG treatments (Table 2). Sheep were not removed from the plots if it rained during grazing. In winter 2011 WSG treatment plots were split and half the area grazed while the other half remained un-grazed. This made it possible to distinguish yield effects caused by grazing of the crop itself in 2011 and soil physical effects from grazing in previous years. There was no significant effect of winter grazing in 2011 on grain yield (data not shown), and subsequently all grazing treatments were applied to the whole plot. The stubble burn treatments were applied in mid- to late-March of each year as is typical in the region due to wildfire risk in summer and thus had little bearing on soil water accumulation during the summer fallow period. Summer weeds that emerged at the site were controlled with herbicide within 5–10 days of emergence, and all in-crop weeds, foliar diseases and pests were controlled with registered pesticides such that they likely did not affect yield. Synthetic fertilisers were applied as required such that nutrient deficiency did not limit yield.

2.1.3. *Soil and crop measurements*

Soil water was monitored during the summer fallow period using time-domain reflectometry (TDR) soil water probes (Campbell Scientific CS615, Campbell Scientific, Logan, Utah USA) at the soil surface (75 and 150 mm depth) and a neutron moisture meter (NMM) for the subsoil (0.1–1.8 m depth). Prior to seeding each year two soil cores (42 mm diameter) were taken per plot to a depth of 1.8 m and segmented into depth 0–0.1, 0.1–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, 0.8–1.0, 1.0–1.3, 1.3–1.6 m. Additional cores were taken for 0–0.1 m depth, and cores were bulked according to depths. Soil from each depth increment was analysed for mineral N (NH_4 and NO_3)

Grain yield was measured using a plot header harvesting only the middle four rows of each seeding run to remove edge effects from rows adjacent to tram tracks. Grain yields were also measured by hand harvesting large areas (>1.0 m^2) of crop and threshing which also allowed total dry matter production, harvest index and amount of the residue returned to plots prior to grazing to be calculated. Wheat grain protein and moisture content was estimated by NIRS, and moisture content was used to standardise grain yields at 12.5% moisture. The amount of stubble present in plots was measured after grazing to calculate how much sheep had consumed.

At the end of each summer fallow period, all residues were removed from a 1 m^2 area in each plot and infiltration rates measured using a drip infiltrometer (McCallum et al., 2004). Surface soil strength was measured at 10 positions between rows and six positions within rows in each plot using a hand-held penetrometer (Zoli Maurizio Geotester, Zoli Maurizio, Alfonsine, Italy) with a blunt 6.35 mm diameter tip which recorded the maximum resistance to penetration for the tip to 6 mm depth. Soil strength was measured on wet soil in areas where water infiltration had been measured 40 min after water infiltration measurements had finished. Bulk density (0–50 mm) was measured in the wet areas using sharpened brass rings forced carefully into the soil and removed for drying at 105 °C.

2.2. Experiment 2—Condobolin

2.2.1. Site description

The second experiment was conducted on a red chromosol with little slope near Condobolin in central west NSW (S 33.57°, E 147.23°, 198 m ASL) which has mean (1963–2013) annual rainfall of 452 mm, 246 mm of which fall during the growing season. A rain-gauge at the site was read following each rainfall event.

2.2.2. Treatments and experimental design

Additional factors were considered at Condobolin in a non-factorial experiment with the following treatments;

Nil graze, stubble retained (NGSR)
Nil graze, stubble mown and removed (NGSM)
Nil graze, additional stubble added (NGSA)
Moderate graze, stubble retained (MGSR)
Heavy graze, stubble retained (HGSR)
Heavy graze, stubble retained & summer weeds not controlled (HGSRW—2012 only)

Each treatment was replicated four times in a randomised complete block design. Treatments were imposed in December 2009 after harvest in a field which carried just under 3 t/ha of wheat stubble, and reimposed on the same plots annually to measure cumulative responses. Plots were 10.5 × 28 m and individually fenced, the fences being erected and removed each year so that all operations except for the stubble treatments were conducted using commercial farm equipment and controlled traffic.

All crops were inter-row sown using a 9 m wide commercial Deep Blade System Auseeder (Ausplow, Cockburn Central, WA Australia). This was fitted with parallelogram seeding units comprised of high breakout tines with 13 mm knife points and press wheels, set at 250 mm row spacing. Cereal crops (wheat, barley, wheat) were sown in May each year, a common sequence following a period of legume-based pasture. Merino ewes grazed the stubbles of treatments MGSR, HGSR and HGSRW in December each year, with grazing duration sufficient to reduce the stubble to about 70% of the ungrazed level in treatment MGSR and 50% in treatments HGSR and HGSRW. The NGSM treatment was designed to separate the effects of stubble removal and animal treading. The stubble was mown at a height of 0.05 m with a walk-behind sickle-bar mower and the cut stubble was carefully removed, minimising surface soil disturbance. The removed stubble was spread on NGSA plots to give a treatment with greater stubble cover.

In all treatments other than HGSRW, summer weeds that emerged at the site were promptly controlled with herbicide. Crop weeds, foliar diseases and pests were controlled with registered pesticides such that they likely did not affect yield.

2.2.3. Crop and soil measurements

Soil water was monitored during the fallow and crop growth periods using a neutron moisture meter (Model 503DR, CPN International, Martinez, CA, USA) read at 0.2 m increments from 0.1 to 1.3 m depth, with two access tubes per plot. Soil water contents were calculated using locally derived linear calibration regressions which accounted for 87% of the variance.

Prior to seeding each year, five soil cores (37 mm diameter) were taken per plot to a depth of 0.9 m, segmented into depths 0–0.1, 0.1–0.3, 0.3–0.5, 0.5–0.7, 0.7–0.9 m and bulked according to depths. Soil from each depth increment was analysed for mineral N (NH_4 and NO_3) and for gravimetric moisture content.

The amount of stubble present in each plot was measured after harvest each year and before and after the imposition of the stubble and grazing treatments by collecting the stubble from two quadrats of 0.375 m^2.

Grain yield was measured by harvesting a 1.8 × 27 m strip from the centre of each plot. Wheat grain protein and moisture content was estimated by NIRS, and moisture content was used to standardise grain yields at 12.5% moisture.

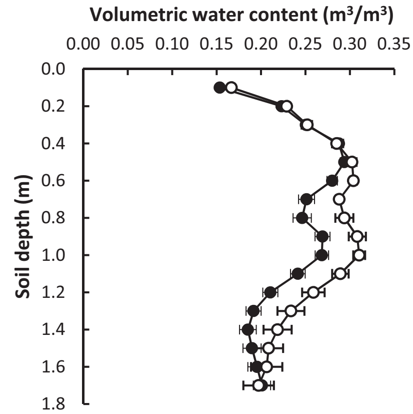

Fig. 2. Volumetric soil water content down the soil profile of the nil graze (○) and combined grazed treatments (●) on 16 March 2010 in Phase 1 of the Temora experiment. Error bars are +/− standard error of means and means with overlapping bars are unlikely to be significantly different.

2.3. Statistical analysis

All data at Temora were analysed using a two-way analysis of variance (ANOVA) in randomised blocks with grazing and stubble treatment as factors in the GenStat 15 software package (VSN International Ltd.). All data at Condobolin were analysed using a one-way ANOVA in randomised blocks in the GenStat 15 software package. Significance is assumed at the 95% confidence level and tests of mean separation were made using Fisher's least significant difference test calculated at the 95% confidence level.

3. Results

3.1. Experiment 1—Temora

The set-up year of Phase 1 (2009) received well below average in-crop rainfall (182 mm) and winter grazing of the crop reduced yield by 0.4 t/ha and protein increased accordingly (Table 3). During the first summer fallow period at the end of 2009, 313 mm of rain fell, including five significant individual events (Fig. 1). The nil graze treatment accumulated more water during the summer fallow period following large and intense rain in mid-February and early March (Table 3). The extra water accumulated was stored deep in the profile (Fig. 2), and there was no difference in soil water content measured at the surface by TDR between nil graze or grazed treatments (Fig. 1). Grazing reduced infiltration rates measured at the end of the summer fallow period. Additional infiltration measurements were made in the un-grazed farmer's field (low residue cover ~1.6 t/ha of a drought-affected canola crop) surrounding the experiment and rates were also found to be low (mean 11 mm/h, standard error = 2). Despite the differences in plant-available water prior to sowing in 2010, in-crop rain (460 mm) was sufficient to sustain crop growth and there were no significant differences in crop yield among the grazing treatments (Table 3) or stubble burn treatments (data not shown). Differences in plant-available water persisted at maturity (data not shown), but heavy rain during the summer of 2010–2011 (477 mm) filled the soil profile and had all but removed the differences prior to sowing in 2011.

Table 3
Stubble remaining after grazing in December of the previous year, steady-state infiltration rate at the end of summer, soil bulk density, soil strength, plant available water (PAW) and mineral N prior to sowing, wheat grain yield and protein in Phase 1 of the Temora experiment.

	Stubble remaining after summer grazing (t/ha)	Summer infiltration rate (mm/h)	Bulk density 0–50 mm (Mg/M^3)	Soil strength 0–10 mm (KPa)	PAW at sowing (mm)	Mineral N at sowing (kg/ha)	Grain yield (t/ha)	Grain protein (%)
2009—Wheat (cv. Gregory)								
Nil graze	–	–	–	–	20	143	1.6	14.4
Stubble graze	–	–	–	–	20	143	1.6	14.6
Winter and Stubble Graze	–	–	–	–	20	143	1.2	14.9
P-value	–	–	–	–	–	–	<0.001	0.006
LSD (P = 0.05)	–	–	–	–	–	–	0.2	0.33
–								
2010—Canola (cv. Tawriffic)								
Nil graze	5.4	33	1.22	222	155	178	4.1	–
Stubble graze	0.8	20	1.23	365	110	205	4.2	–
Winter and Stubble Graze	0.8	16	1.25	516	99	279	4.0	–
P-value	–	0.041	0.549	0.005	<0.001	0.014	0.62	–
LSD (P = 0.05)	–	11	NS	135	19	53	NS	–
–								
2011—Wheat (cv. Bolac)								
Nil graze	8.0	102	1.35	298	201	93	4.6	13.1
Stubble graze	4.0	49	1.38	355	183	126	4.6	13.5
Winter and Stubble Graze	4.0	44	1.40	460	187	199	5.2	13.0
P-value	–	0.006	0.819	0.010	0.011	0.001	<0.001	0.158
LSD (P = 0.05)	–	29	NS	91	11	49	0.2	0.6
–								
2012—Wheat (cv. Wedgetail)								
Nil graze	9.8	–	–	–	203	99	4.7	10.5
Stubble graze	4.2	–	–	–	192	144	4.8	10.9
Winter and Stubble Graze	3.8	–	–	–	196	168	4.7	11.2
P-value	–	–	–	–	0.127	0.005	0.768	0.022
LSD (P = 0.05)	–	–	–	–	NS	38	NS	0.5

Table 4
Stubble remaining after grazing in December of the previous year, steady-state infiltration rate at the end of summer, soil bulk density, soil strength, plant available water (PAW) and mineral N prior to sowing, wheat grain yield and protein in Phase 2 of the Temora experiment.

	Stubble remaining after summer grazing (t/ha)	Summer infiltration rate (mm/h)	Bulk density 0–50 mm (Mg/M^3)	Soil strength 0–10 mm (KPa)	PAW at sowing (mm)	Mineral N at sowing (kg/ha)	Grain yield (t/ha)	Grain protein (%)
2010—Wheat (cv. Bolac)								
Nil graze	–	–	–	–	48	185	6.9	13.6
Stubble graze	–	–	–	–	48	185	6.9	13.4
Winter and Stubble Graze	–	–	–	–	48	185	7.5	13.3
P-value	–	–	–	–	–	–	0.012	0.419
LSD (P = 0.05)	–	–	–	–	–	–	0.4	NS
–								
2011—Canola (cv. 45Y82)								
Nil graze	11.5	59	NA	308	145	92	3.4	–
Stubble graze	5.5	36	NA	494	143	94	3.3	–
Winter and Stubble Graze	5.5	34	NA	563	135	105	3.1	–
P-value	–	0.022	–	0.002	0.338	0.696	0.114	–
LSD (P = 0.05)	–	16	–	111	NS	NS	NS	–
–								
2012—Wheat (cv. Bolac)								
Nil graze	7.4	79	1.18	150	138	73	4.8	10.5
Stubble graze	3.3	36	1.28	360	140	76	4.9	10.3
Winter and Stubble Graze	3.1	24	1.27	524	132	90	4.8	10.5
P-value	–	0.003	0.059	0.006	0.438	0.032	0.451	0.595
LSD (P = 0.05)	–	24	NS	168	NS	13	NS	NS

Table 5
Stubble remaining after grazing in the previous fallow, water stored during the fallow, and mineral N prior to sowing, wheat grain yield and protein in the experiment at Condobolin.

	Stubble remaining after summer grazing (t/ha)	Fallow water storage (mm)	Mineral N at sowing (kg/ha)	Grain yield (t/ha)	Grain protein (%)
2010—Wheat (cv. Livingston)					
Nil graze, stubble retained	1.9	125	183	4.6	11.8
Nil graze, stubble mown and removed	1.8	128	199	4.5	11.8
Nil graze, stubble added	3.7	136	134	4.7	11.8
Moderate graze, stubble retained	1.4	126	157	4.7	11.8
Heavy graze, stubble retained	0.9	131	181	4.4	11.8
P-value	<0.001	0.17	0.006	0.001	0.99
LSD (P = 0.05)	0.2	NS	32	0.2	NS
2011—Barley (cv. Hindmarsh)					
Nil graze, stubble retained	3.2	−3	115	2.5	10.4
Nil graze, stubble mown and removed	0.8	−19	120	2.1	10.5
Nil graze, stubble added	6.4	16	108	2.5	10.7
Moderate graze, stubble retained	2.8	−3	120	2.3	10.6
Heavy graze, stubble retained	2.2	−11	137	2.2	11.1
P-value	<0.001	<0.001	0.58	0.003	0.31
LSD (P = 0.05)	0.4	11	NS	0.2	NS
2012—Wheat (cv. Livingston)					
Nil graze, stubble retained	3.3	96	90	1.72	9.0
Nil graze, stubble mown and removed	0.5	90	116	1.83	9.7
Nil graze, stubble added	6.1	98	76	1.65	9.0
Moderate graze, stubble retained	1.6	93	103	1.78	8.9
Heavy graze, stubble retained	1.2	99	85	1.84	9.7
Heavy graze, stubble retained & summer weeds not controlled	1.2	74	87	1.49	9.6
P-value	<0.001	0.076	0.049	0.02	0.04
LSD (P = 0.05)	0.4	NS	23	0.18	0.6

Winter and stubble grazing significantly increased the amount of soil mineral N available compared to the other treatments prior to sowing in 2010, and this difference persisted in 2011 (Table 3). In 2012 both the SG and WSG treatments increased mineral N relative to the NG treatment

In 2011 there was no difference in grain yield between these two halves of the WSG plots that had been split for grazing in 2011 (results not shown), and the WSG treatment out-yielded the NG and SG treatment by 0.6 t/ha.

Grazing again reduced infiltration rates in 2011, but rates in all treatments were much higher than at the start of 2010. Likewise grazing increased soil strength in both 2010 and 2011.

Summer fallow rain preceding the 2012 cropping season was also well above average (462 mm) which filled the soil profile and removed the differences in plant available water (Table 3). In-crop rainfall was well below average (175 mm) and there was no significant effect of grazing on grain yield. The WSG treatment had higher grain protein than the NG treatment, reflecting the higher soil available N. In 2012 burning stubble increased yield from 4.6 to 4.9 t/ha ($P = 0.003$) and there was an interaction with grazing ($P = 0.037$) such that burning increased yield to a greater extent in the NG treatment (0.6 t/ha) compared to both of the grazed treatments (0 and 0.4 t/ha for SG and WSG respectively). This was the only time during the experiment that there was a significant interaction or main effect of burning on any parameter.

In the set-up year of Phase 2 (2010), winter grazing of the crop increased yield by 0.6 t/ha (Table 4). There were no effects of grazing treatments on yield in either 2011 or 2012. Grazing reduced infiltration and increased soil strength in both 2011 and 2012, but not to levels likely to reduce fallow efficiency or decrease crop yield. Winter and stubble grazing significantly increased mineral N prior to sowing in 2012.

3.2. Experiment 2—Condobolin

There was 338 mm of summer fallow rain prior to the 2010 growing season. There was no effect of grazing or addition or removal of stubble on soil water storage, but mineral N at sowing was lower where stubble was added and higher where it was removed (Table 5). In the wet growing season of 2010 (286 mm) the heavily grazed treatment yielded less than all other treatments.

During the 2010/2011 summer fallow (298 mm rain) treatments with more stubble stored more soil water, but there was no difference between the NGSS and HGSR treatments. In the relatively dry growing season of 2011 (189 mm) the higher water storage under the NGSR and NGSA treatments resulted in higher yields.

During the 2011/2012 summer fallow (461 mm) the HGSRW treatment accumulated less soil water than the other treatments ($P = 0.076$). The NGSA treatment had 40 kg/ha less mineral N than the NGSM treatment. The 2012 growing season was also dry (177 mm) and the HGSR and NGSM treatments yielded marginally more than the nil graze treatment and also had higher grain protein content (Table 5).

4. Discussion

4.1. Effects of grazing stubble during the summer fallow

Over the four years of the Temora experiment, grazing stubbles during summer consistently affected soil properties – reducing infiltration, increasing bulk density and soil strength, but rarely to levels that were detrimental to soil water capture, crop growth or grain yield. Infiltration rates generally remained well in excess of usual rainfall intensity in the region (Australian Government Bureau of Meteorology, 2013) and soil strength did not reach levels detrimental to plant growth (>2000 KPa). This finding is consistent with the conclusions of a number of recent studies elsewhere in different systems (Allan et al., 2016; Barsotti et al., 2013; Bell et al., 2011; Lenssen et al., 2013; Stavi et al., 2015).

The only negative yield responses due to grazing stubbles was in the HGSR treatment at Condobolin in 2010 and 2011. In this treatment the amount of stubble remaining (0.9 t/ha in 2010, 2.2 t/ha in 2011) was at or below the 70% cover or 2.0 t/ha level commonly recommended for the prevention of run-off and soil erosion on clay soils (Felton et al., 1987). This was also the case at Temora when the greatest potentially negative impact on crop production due to grazing occurred following the 2009 growing season, when the amount of stubble remaining in the grazed treatments at the start of 2010 (0.8 t/ha) was below known thresholds for prevention of run-off and soil erosion. In this second instance, grazing stubble reduced soil water storage during the 2009/2010 summer fallow period by 50 mm. The additional soil water in the NG treatment was stored at depth, indicating that the difference in accumulation was due to improved infiltration in the presence of stubble, rather than reduced evaporation. It is unlikely that the relatively small differences in residue cover could slow evaporation sufficiently to create such large differences in soil water given the frequency of rainfall events (Bond and Willis, 1970; Verburg et al., 2012). This hypothesis is supported by measurements of soil water at the surface by TDR which showed no difference between the NG or WSG and SG treatments following rainfall events.

The inferior infiltration in the grazed treatments was likely to be due to higher rain-drop impact damage due to reduced stubble cover (Felton et al., 1987; Freebairn and Boughton, 1981) rather than soil physical effects due to trampling, as infiltration rates in the surrounding un-grazed farmer's field (low stubble cover ∼1.6 t/ha of a drought-affected canola crop) were comparable to measurements in the stubble grazed treatment (11 cf 20 mm/h; respectively). Further evidence to support this hypothesis can be found at Condobolin in 2011, when removal of stubble by sheep grazing (HGSR) or mowing and removing (NGSM) had equivalent negative effects on soil water storage and crop yield. This implies trampling by sheep does no additional damage beyond that due to removal of soil cover.

In the case of Temora in 2010, any influence of reduced soil water storage on grain yield was negated by the wet growing season of 2010 and summer fallow period of 2010/2011. The circumstances of actual (Condobolin, 2010) and potential (Temora, 2010) negative impact on crop production (grazing below threshold cover) also reflect the circumstances of the only site year reported by Allan et al. (2016) where a yield penalty was recorded, at which pasture residues were grazed to 1.8 t/ha and 38% cover.

In Phase 1 of the Temora experiment there was a trend for the SG treatment to accumulate more mineral N during the summer fallow compared to the NG treatment, although this difference only became significant in 2012. There was also more mineral N in the moderate grazed treatment compared to the nil graze treatment at Condobolin in 2012. There are several mechanisms that could collectively be responsible for this difference. Crop residues and vegetative biomass consumed by sheep are digested by the animal and the majority (up to 80%; White et al., 1997) of the N is commonly returned to the soil as urea in urine, which under warm summer temperatures would rapidly hydrolyse to ammonia before nitrifying (Haynes and Williams, 1993). Much of the carbon in plant residues consumed by animals is emitted in gaseous form (CO_2 and CH_4) and lost from the system, or separately excreted to plots as faeces (Freer et al., 1997). This allows N to remain in mineral form and available to crops, whereas in NG treatments the organic N in stubble is likely to be immobilised by decomposing microbes (Mary et al., 1996). Stavi et al. (2015) found that grazing of wheat residues increased total soil organic carbon content and labile carbon content, which over time would increase the capacity for soils under grazing to mineralise N. No measurements of soil carbon have been made in this study, but these would be a helpful starting point to elucidate the mechanisms behind the observed increase in mineral N. At Condobolin, there was significantly more mineral N in the NGSS treatment compared to the NGSA treatment in both 2010 and 2012, implying that immobilisation of N by decomposing wheat residues may be the dominant factor driving measured differences in mineral N.

Previous studies have speculated that increased mineral N is a possible benefit from grazing cropping fallows (Barsotti et al., 2013; Hatfield et al., 2007), but few have demonstrated it and none have elucidated which mechanisms may be responsible, or their relative importance. Lenssen et al. (2013) and Sainju et al. (2014) reported significantly lower soil nitrate in grazed treatments compared to tilled or chemical fallow, and Allan et al. (2016) report inconsistent responses in levels of soil mineral N to grazing. The discrepancy between our results and previous studies is readily explained by the focus or retention of fallow weeds as a treatment effect in previous studies. Summer fallow weeds are known to greatly reduce levels of soil mineral N available prior to the planting of subsequent crops (Hunt et al., 2013; Kirkegaard et al., 2014) and grazing them is unlikely to substantially reduce water or N use (Fischer, 1987). Further research into the effect of grazing of crop residues on N availability to crops could potentially be rewarding given the economic and environmental imperative to improve the nutrient use efficiency of cropping systems.

A question remains regarding the extrapolation of the results from the short grazing duration with high stocking rates used in the Temora experiment to commercial paddocks where stocking rates may be lower, grazing duration longer and spatially variable. Whilst it is impossible to answer this question definitively, in theory as long as grazing intensity is thought of in terms of stocking rate and duration (i.e. sheep/ha days) results should be relevant to commercial practice. This assumption is supported by the similar findings arising from paddock scale experiments at lower stocking rates at Condobolin, and also reported by Allan et al. (2016).

4.2. Effects of grazing crops during winter

Winter grazing of crops during the vegetative stage at Temora had variable impact on yield in a manner consistent with the review of grazed crops by Harrison et al. (2011). Whilst the additional grazing in winter when soils are generally wet significantly increased soil strength relative to the SG treatment, it did not increase it to an extent likely to be detrimental to plant growth (>2000 KPa). It is unlikely that any of the observed yield effects from grazing in winter were due to soil physical effects. They were more likely due to differences in plant growth in response to defoliation, and possibly to increased soil mineral N in the WSG treatments (see below). This is supported by results from 2011 in which WSG plots were split and only half grazed in order to separate soil physical effects from previous grazing from effects of defoliation and there was no difference in yield between the two halves.

Grazing in winter increased the amount of soil mineral N measured prior to sowing in all years of the experiment in Phase 1 and in 2012 in Phase 2. This resulted in the WSG treatment having higher grain protein at equivalent grain yield levels in Phase 1 in 2012, and is also the probable explanation for the higher grain yield of the WSG treatment in 2011. This stands at odds with the study of Franzluebbers and Stuedemann (2013) who found that cattle grazing cover crops gave variable responses to soil mineral N over a six year experiment, but that at the conclusion of the experiment mineral N levels were lowered by grazing. There are additional mechanisms not at play in the study of Franzluebbers and Stuedemann (2013) and further to those discussed in the section on stubble grazing above that could collectively be responsible for this increased mineral N in response to vegetative grazing. In the first year of Phase 1, grain yield of the WSG treatment was lower and thus N removal in grain was lower, leaving more N in the soil for the following season. Secondly, winter grazed crops accumulate less total dry matter by maturity due to defoliation (Virgona et al., 2006), and thus plant N uptake is less in comparison to NG and SG crops. Thus more N would be left in the soil for subsequent crops in these treatments. Reduced biomass accumulation in the

WSG treatment also means less carbon-rich residues and roots are returned to the soil surface which could reduce N immobilisation (Holland and Detling, 1990). Residues of vegetatively grazed wheat crops also tend to have higher N content which has been shown to hasten the release of N from residues (Assmann et al., 2014).

4.3. Effects of burning residues

Wheat yield responses to either burning or retaining stubble were generally similar to those reported by Kirkegaard (1995) and Giller et al. (2015) in which the response related to the level of growing season rainfall. In general yield increases with retained stubble are expected in drier seasons as a result of water conservation while yield decreases occur in wetter seasons due to factors such as increases in N immobilisation, stubble borne diseases and colder temperatures in winter above the stubble. The only exception to this was in Phase 1 in 2012 where burning increased yield by 0.5 t/ha despite very low growing season rainfall (178 mm). There are several possible reasons for this in the experiment reported here. Firstly, it was the only year in the experiment in which wheat was grown on wheat, and burnt treatments had less tan-spot (*Pyrenophora tritici-repentis*) infection during vegetative growth. However, tan spot infection during vegetative stages in SNSW is very common and rarely affects yield. Visually, burnt treatments appeared to have less frost induced sterility (FIS) than those in which stubble was retained, but measurements of FIS showed no significant difference (data not shown).

5. Conclusions

Our data support the conclusions of Bell et al. (2011) reporting that physical effects from grazing sheep trampling soil tend to be shallow and transient and reductions in subsequent crop yield are rare. These findings give confidence that provided a critical level of soil cover is maintained (recommended >70% or >2.0 t/ha of cereal stubble), livestock can be retained within modern conservation cropping systems without compromising crop performance, and may continue to provide production and business risk benefits in the future. In SNSW crop residues are frequently produced that are well in excess of levels required to prevent soil erosion, and in more favourable seasons reduce crop yield (Giller et al., 2015; Kirkegaard et al., 1994). Reduction of residues by grazing is preferable to alternate means of residue management (e.g. burning, baling, tillage or mulching) which all carry financial and environmental costs.

Grazing of stubbles and crops appeared to make more mineral N available to crops which has obvious implications for crop growth, grain yield and protein and is perhaps an overlooked benefit of keeping livestock in stubble retained farming systems. Further research is necessary to determine by what mechanism this effect is operating, and how it could be used to greater advantage in mixed farming systems in the longer term. Understanding these processes will be particularly important given the decreasing area and quality of legume-based pastures in NSW and the increasing reliance on expensive fertiliser N for crop production (Angus and Peoples, 2012).

Acknowledgements

This research was funded by the Grains Research and Development Corporation (GRDC) of Australia (Projects FLR00005, CWF00013, CSP00111 and CSP00174). Funding for the Temora experiment was provided through FarmLink Research, funding for the Condobolin experiment was provided through Central West Farming Systems. We thank the Catch More, Store More, Grow project steering committee (Jason Coleman, Greg Condon, Chris Duff, Derek Ingold, James Ingrey, Geoff Lane, John Pattison, Jamie Pursehouse, Michael Sinclair, Rob Taylor, Craig Warren) for their advice on conduct of the experiments; Peter, Lynne and Jason Coleman for hosting the experiments; Laura Goward, Brad Rheinheimer, Tony Pratt, Mitchell Cuell, James Holding and Mitch Allen for providing technical assistance; Steve Henry for assisting with soil characterisations.

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