CSIRO PUBLISHING

Crop & Pasture Science, 2015, **66**, 308–317
http://dx.doi.org/10.1071/CP14273

Forage and grain yield of grazed or defoliated spring and winter cereals in a winter-dominant, low-rainfall environment

Alison. J. Frischke[A,C], *James R. Hunt*[B], *Dannielle K. McMillan*[A], *and Claire J. Browne*[A]

[A]BCG, PO Box 85, Birchip, Vic. 3483, Australia.
[B]CSIRO Agriculture Flagship, GPO Box 1600, Canberra, ACT 2601, Australia.
[C]Corresponding author. Email: alison@bcg.org.au

Abstract. In the Mallee region of north-western Victoria, Australia, there is very little grazing of crops that are intended for grain production. The success of dual-purpose crops in other regions in south-eastern Australia with higher and more evenly distributed rainfall has driven interest in assessing the performance of dual-purpose cereals in the region. Five experiments were established in five consecutive years (2009–13) in the southern Mallee to measure the forage production and grain yield and quality response in wheat and barley to grazing by sheep or mechanical defoliation. The first three experiments focused on spring cultivars sown from late April to June, and the last two on winter cultivars planted from late February to early March. Cereal crops provided early and nutritious feed for livestock, with earlier sowing increasing the amount of dry matter available for winter grazing, and barley consistently produced more dry matter at the time of grazing or defoliation than wheat. However, the grain-production response of cereals to grazing or defoliation was variable and unpredictable. Effects on yield varied from –0.7 to +0.6 t/ha, with most site × year × cultivar combinations neutral (23) or negative (14), and few positive (2). Changes in grain protein were generally consistent with yield dilution effects. Defoliation increased the percentage of screenings (grains passing a 2-mm sieve) in three of five experiments. Given the risk of reduced grain yield and quality found in this study, and the importance of grain income in determining farm profitability in the region, it is unlikely that dual-purpose use of current cereal cultivars will become widespread under existing grazing management guidelines for dual-purpose crops (i.e. that cereal crops can be safely grazed once anchored, until Zadoks growth stage Z30, without grain yield penalty). It was demonstrated that early-sown winter wheat cultivars could produce more dry matter for grazing (0.4–0.5 t/ha) than later sown spring wheat and barley cultivars popular in the region (0.03–0.21 t/ha), and development of regionally adapted winter cultivars may facilitate adoption of dual-purpose cereals on mixed farms.

Additional keywords: barley, grazing, vernalisation, wheat.

Received 18 August 2014, accepted 2 March 2015, published online 31 March 2015

Introduction

Rainfall in the Mallee region of north-western Victoria, Australia, is highly variable. Annual rainfall averages 356 mm at the township of Birchip in the south of the region; however, it varies annually from 126 to 678 mm. Consequently, agricultural production in the region is inherently risky. Over the last 20 years, there has been widespread adoption of continuous crop production using no-till crop establishment practices (Llewellyn *et al*. 2012) in the Victorian Mallee, leading to a decline in sheep numbers. The area planted to grain crops has increased by 12% from 1.47 Mha in 2001 to 1.67 Mha in 2011, whereas sheep numbers have decreased by 25% from 1.1 million to 0.8 million during the same period (ABARES 2014). As crop production has intensified, so have crop input costs, and farm businesses are now more exposed to financial loss when production is affected by extreme weather such as drought, heat and frost (van Rees *et al*. 2015). For most farm businesses, a livestock enterprise, mainly sheep, continues to be important for mitigating risk of seasonal production and commodity price variability (Bell and Moore 2012).

Stocking rates in the region are very conservative because of high cropping intensity and the low and variable rainfall, and are typically in the order of 2–6 dry sheep equivalents (DSE)/ha (Robertson 2001). Rainfall distribution in the region is Mediterranean and grain crops are grown during the cool, wet months from April to October. Spring wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), canola (*Brassica napus*) and grain legumes are grown in sequence with annual pastures, which traditionally are based on medic (*Medicago* spp.) but also include volunteer broadleaf and grass species (Cooke *et al*. 1989). More recently, sown annual pastures of vetch (*Vicia* spp.) kept free of annual grass weeds and terminated in spring have become the dominant pasture type (Kirkegaard *et al*. 2014). Stock graze pastures from late autumn to early summer, and following harvest of grain, crops graze on crop stubbles, consuming spilt grain and plant residues (Thomas *et al*. 2010).

A major limitation to increased livestock productivity through higher stocking rates is the seasonal scarcity of forage that occurs in late autumn to early winter, referred to as the winter feed-gap. During this time, the previous season's pastures and crop stubbles are exhausted, and legume-based pastures, which grow slowly in the cooler months, are yet to reach a stage at which they can be safely grazed. This feed-gap is largely an outcome of the Mediterranean rainfall distribution, but in the last two decades has worsened due to declining autumn rainfall in the region (Pook *et al*. 2009; Cai *et al*. 2012). If no feed is available during this time, growers must destock, find agistment or provide supplementary feed, all of which reduce profitability of the livestock enterprise.

In regions of south-eastern Australia with higher rainfall of temperate distribution, such as south-eastern New South Wales (NSW), south-western Victoria and Tasmania, juvenile grain crops are grazed by stock during winter to alleviate the scarcity of feed at this time. This can be done with little compromise to grain yield provided stock are removed before the start of stem elongation (Virgona *et al*. 2006; Harrison *et al*. 2011). In these regions, locally adapted winter cereals are used and are referred to as 'dual-purpose crops' (Radcliffe *et al*. 2012). Winter cereals have a vernalisation requirement, meaning that they need to be exposed to cold temperatures (4°–18°C) for a certain period of time before spike development and stem elongation (Zadoks growth stage Z30; Zadoks *et al*. 1974) begins. This means they can be sown much earlier than spring wheats (as early as late February) and will not flower too early and risk exposure to frost. Winter wheats also spend much longer in the tillering phase before Z30, and they can thus be safely grazed for longer than spring cultivars if managed as a dual-purpose crop. No active breeding has been directed at winter cereals suited to the alkaline soils of the Mallee or their endemic production constraints (cereal cyst nematode, boron toxicity, salinity). All wheat and barley breeding for the region has focused on cultivars with mid–fast maturity, with development moderated by weak photoperiod sensitivity (Eagles *et al*. 2009).

In the Victorian Mallee region, there is very little grazing of crops that are intended for grain production. If crops are grazed, it is usually opportunistic, e.g. sacrificial grazing of drought- or frost-affected crops (Bell *et al*. 2009). The success of dual-purpose crops in other regions has driven interest in assessing the suitability of grazing cereals in low-rainfall areas such as the Victorian Mallee.

Moore (2009) used simulation to identify the potential value of dual-purpose wheats across southern Australia, and compared a winter genotype with a mid–fast-maturing spring genotype. He found that in the Mallee at Walpeup, in years that allowed early sowing, the winter genotype not only produced much more forage than the spring type (sufficient to sustain an extra 419 DSE grazing days (DSE-days)/ha), but also had a significant grain yield advantage over the spring genotype (1.02 t/ha when grazed, 1.22 t/ha ungrazed). The spring genotype was found to produce useful amounts of forage (146 DSE-days/ha), highlighting the potential for the practice of grazing grain crops to overcome the winter feed-gap in the Mallee. Also using simulation, Harrison *et al*. (2012) found that grain yield penalties due to grazing were less in years of lower yield potential, which adds further support for the likely success of the practice in environments of low and variable rainfall. Virgona *et al*. (2006) measured a grain yield increase in dry conditions after grazing long-season wheat in southern NSW, attributed to the delay in maturity of early-sown grazed crops, resulting in deferred water use and ability of crops to respond to late rains. An experimental study from 2005 to 2007 on the Eyre Peninsula of South Australia, which has a low and Mediterranean rainfall similar to the Mallee, found that the effects of defoliation ranged from no grain yield reduction (particularly in seasons with low yield potential) to losses of 22–55% (0.2–1.0 t/ha) when locally adapted spring wheats were defoliated (Latta 2015). However, that study did find variation in the ability of spring wheat genotypes to maintain grain yield following defoliation.

Considering the findings of the above simulation and field studies, this paper experimentally evaluates fodder production and grain-yield recovery of commonly grown and locally adapted mid–fast-maturing spring wheat and barley cultivars, and winter cultivars from a range of sources. It does so using guidelines developed in other regions where it has been established that stock can be introduced to cereal crops intended for grazing at around the 3-leaf (Z13) stage or when plants are anchored. The risk of incurring a grain yield penalty is reduced when stock are removed before the embryonic ear begins to move up the stem at the start of stem elongation (Z30). Greater yield penalties may be incurred as crops are grazed later into the season, especially beyond Z31, and as grazing pressure increases through stocking rate or duration of the grazing period, which affects the biomass remaining at the end of grazing (Virgona *et al*. 2006; Kelman and Dove 2009). For grazing of cereals to be adopted in the Mallee, experiments would need to demonstrate that useful amounts of forage could be provided at a time when feed availability is generally low, and that the risk of reducing grain yield and quality by grazing would be low, particularly in low-yielding seasons.

Materials and methods

The study comprised five experiments run from 2009 to 2013 in the southern Mallee of Victoria. All experiments evaluated the early dry matter (DM) production and quality of a range of wheat and barley cultivars, and their ability to maintain grain yield and quality following defoliation. Expts 1–3 evaluated spring cereals commonly grown in the region, and Expts 4 and 5 evaluated winter cereals selected for other regions. Soil chemical properties, plant-available water before sowing and April–October (growing-season) rainfall at each experimental site are provided in Table 1. Mean growing-season rainfall for all sites is ~240 mm. All sites exhibited toxic levels of boron (>9 mg/kg) in the subsoil, with the exception of Woomelang and Curyo where boron was not measured. Electrical conductivity (>0.7 dS/m) and chloride (>600 mg/kg) exceeded levels conducive to plant growth at Woomelang, Culgoa and Birchip.

General methods

Experiments 1–5 were conducted in consecutive years 2009–13. Expts 1 and 2 were strip-plot designs with grazing as the main plot and cultivar as the split. Expts 3–5 were blocked randomised designs. All experiments had four replicates. Seeding rates in all experiments were adjusted for seed size, with an aim to establish 150 plants/m^2, reflecting the district practice for sowing rate of cereal crops. All experiments were sown with a plot seeder with

Table 1. Soil chemical properties, starting soil water and April–October rainfall of experimental sites 2009–13
NA, Not available

	Depth (m)	Expt 1 Woomelang 2009	Expt 2 Culgoa 2010	Expt 3 Corack 2011	Expt 4 Birchip 2012	Expt 5 Curyo 2013
Surface texture		Sandy loam	Clay loam	Clay loam	Clay loam	Sandy loam
pH(H_2O)	0–0.1	9.0	8.3	8.6	8.3	9.0
Colwell P (mg/kg)	0–0.1	15	34	13	32	25
P buffering index	0–0.1	75	69	120	81	119
Nitrate-N (kg/ha)	0–1.0	158	16	15	53	83
Organic C (%)	0–0.1	0.9	1.0	0. 8	1.0	1.0
Boron (mg/kg)	0–0.1	1.3	2	1	1	NA
	0.1–0.4	NA	6	47	2	NA
	0.4–0.7	NA	13	21	9	NA
	0.7–1.0	NA	17	39	19	NA
Chloride (mg/kg)	0–0.1	NA	NA	18	15	50
	0.1–0.4	NA	NA	10	7	208
	0.4–0.7	NA	NA	31	1	459
	0.7–1.0	NA	NA	370	11	437
Electrical conductivity (dS/m)	0–0.1	0.17	0.19	NA	0.08	NA
	0.1–0.4	0.32	0.43	NA	0.09	NA
	0.4–0.7	0.72	0.61	NA	0.31	NA
	0.7–1.0	0.90	0.71	NA	0.60	NA
Plant-available water before sowing (mm)	0–1.0	17	34	88	54	75
Apr.–Oct. rainfall (mm)	NA	209	248	104	146	218

knife-points and press-wheels on a row spacing of 0.3 m, and received starter fertiliser banded with the seed as detailed below. Plots were 1.8 m wide by 12 m long. Standard pre- and post-emergent herbicides were used for weed control at recommended rates, and care was taken to meet all withholding periods before grazing.

Production of DM was measured at Z13–14 just before grazing. All DM production estimates were measured from samples cut to the white line (change in colour from white to green along the stem) along two adjacent 0.5-m sections of crop row at two locations within each plot, totalling 0.6 m^2 in area. Biomass was calculated on an oven-dried moisture content basis (48 h at 70°C).

Feed quality was measured by FeedTest, Agrifood Technology (Werribee, Vic.) laboratories using NIR analysis. These measurements were replicated in Expt 1, but for all subsequent experiments, samples were bulked meaning it was not possible to test for significance between treatments. However, in all experiments, nutritional values were well in excess of those required for growing lambs or lactating ewes.

Grazing treatments were applied using sheep in 2009 and 2010, albeit at stocking rates much higher than those found in the Mallee. However, following a review by Harrison *et al*. (2011) of experiments comparing grazing and mechanical defoliation, which found no difference between the two methods on crop recovery, all treatments in 2011, 2012 and 2013 were defoliated mechanically to simulate grazing using a self-propelled mower cutting crops to 3–4 cm height. After grazing, crops were left to mature.

For all experiments, grain yield was measured using a small-plot harvester. Grain moisture and protein content were estimated using NIR (Infratec 1241 grain analyser; FOSS Analytical, Sweden) and all yields are reported at 12% (delivery standard) moisture. Grain screenings were measured using a slotted 2-mm sieve (local delivery standards allow 5% screenings in most milling wheat and malting barley segregations).

All statistical analyses were conducted using GenStat 13th Edition (VSN International Ltd, Hemel Hempstead, UK).

Experiment 1

This experiment was established near Woomelang (35°40′50″S, 142°39′49″E), in 2009 to evaluate the grazing potential of six commonly grown and locally adapted spring wheat cultivars (Yitpi, Correll, Axe, Wyalkatchem, Young, Derrimut, and Clearfield® Stiletto), and two spring barley cultivars (Buloke and Hindmarsh). Plots 24 m in length were sown into wheat stubble on 7 May with 40 kg/ha of di-ammonium phosphate starter fertiliser (7.2 nitrogen (N), 8 phosphorus (P) kg/ha). Early grazing value (DM production) and feed quality was measured at Z14, just before grazing on 23 June 2009. A fence was erected around one-half of each of the four blocks to split them for grazing (which gave 12-m plots for all treatments), and ten 11-month-old Merino lambs were placed inside the grazing treatment area (67 DSE/ha). Lambs were removed on 26 June 2009 after they had grazed plants to ~1 cm in height. All treatments were harvested on 13 November 2009. Plant density, Z14 DM and feed quality parameters were all analysed as one-way analysis of variance (ANOVA) with cultivar as the only factor in randomised blocks. Yield, protein and screenings were all analysed as a strip-plot design.

Experiment 2

This experiment was established near Culgoa (35°45′06″S, 143 07′45″E) in 2010 to evaluate the grazing potential of six commonly grown and locally adapted spring wheat cultivars

(Axe, Derrimut, Correll, Gladius, Lincoln and Yitpi) and three spring barley cultivars (Hindmarsh, Buloke and Gairdner). Plots were sown into barley stubble on 23 April with 50 kg/ha of mono-ammonium phosphate (MAP) starter fertiliser (5 N, 11 P kg/ha). Despite two applications of α-cypermethrin (a third application was not applied because of the withholding period risk for grazing), damage by the Australian plague locust (*Chortoicetes terminifera*) was so great that the trial was terminated and resown on 2 June with the same cultivars and 43 kg/ha of urea (19.8 N kg/ha). Production of DM was measured at Z13 just before grazing on 5 July 2010. On 6 July, grazed treatment plots were fenced and five 60-kg Merino ewes were placed inside for 3 days (equivalent to 98 DSE/ha). Ewes were removed on 9 July after they had grazed plants to ~2 cm in height. Plots were topdressed with 10 kg/ha of N as urea after grazing. Barley was harvested on 23 November and wheat on 15 December 2010. Plant density and Z13 DM were analysed as a one-way ANOVA with cultivar as the only factor in randomised blocks. Yield, protein and screenings were all analysed as a strip-plot design.

Experiment 3

This experiment was established near Corack (36°11′18″S, 143°1′37″E) in 2011 to evaluate the grazing potential of two commonly grown and locally adapted spring wheat cultivars (Axe and Scout), four spring barley cultivars (Hindmarsh, Commander, Buloke and Oxford) and the winter barley cultivar Urambie. In this experiment, species were blocked and analysed separately. Plots were sown into barley stubble on 29 April with 50 kg/ha of Granulock® Z starter fertiliser (Incitec Pivot Fertilisers, Melbourne; 5.5 N, 11 P, 2 S, 2 Zn kg/ha). Despite heavy falls of summer rain in this season (186 mm in January and 79 mm in February), autumn and winter were very dry, and 18 mm of rain, which fell on 20 May and established the experiment, was the only significant fall until August. Plots were topdressed with 19 kg/ha of N as urea on 17 June, and 12 kg/ha of N as urea on 15 July. All treatments were mechanically defoliated to 3–4 cm at Z14, and additional plots were defoliated later, at Z30, in two cultivars of wheat (Axe and Scout) and barley (Hindmarsh and Commander), to evaluate time of defoliation on crop recovery and production. Production of DM was measured just before defoliation at Z14 on 11 July 2011, and Z30 on 1 August 2011. Barley was harvested on 15 November and wheat on 2 December 2011. Plant density and Z14 DM were all analysed as one way ANOVA in randomised blocks with species analysed separately. Plant density was used as a covariate in all other analyses. Yield, protein and screenings were all analysed as a two-way ANOVA in randomised blocks with cultivar and defoliation as factors. Species were analysed separately, and the two barley cultivars defoliated at Z14 and Z30 analysed separately from those defoliated at Z14 alone.

Experiment 4

This experiment was established near Birchip (35°58′30″S, 142°50′50″E) in 2012 following 56 mm of rain in late February–early March to evaluate the grain yield and grazing potential of early-sown wheat. Five wheat cultivars were sown on 14 March: two winter cultivars, Rosella and EGA Wedgetail; two slow-maturing spring cultivars, Bolac and Forrest; and the commonly grown and locally adapted spring wheat cultivar, Yitpi. Plots were sown into canola stubble with 50 kg/ha of MAP (5 N, 11 P kg/ha) and were topdressed with 41 kg/ha of N as urea on 25 July and again on 8 August 2012. Production of DM was measured and mechanical defoliation to 3–4 cm applied on 16 May when crop growth stages varied between Z23 and Z43. All treatments were harvested on 18 November 2012. Dry matter at defoliation was analysed as a one-way ANOVA in randomised blocks. Yield, protein and screenings were all analysed as a two-way ANOVA in randomised blocks with defoliation and cultivar as factors.

Experiment 5

This experiment was established at Curyo (35°51′14″S, 142°47′26″E) in 2013 following 54 mm rain in mid-February to evaluate the grazing potential of five Australian winter wheat cultivars (Revenue, Rosella, EGA Wedgetail, Wylah and Whistler), and Chinese winter wheat YW443. Plots were sown into chickpea stubble on 26 February 2013 with 30 kg/ha of MAP starter fertiliser (3.3 N, 6.6 P kg/ha). Plots were topdressed with 41 kg/ha of N as urea on 9 July 2013 and a further 83 kg/ha of N as urea on 20 August 2013. Production of DM was measured at Z16 and mechanical defoliation to 3–4 cm applied on 9 July 2013. All treatments were harvested on 27 November 2013. Plant density, Z14 DM and feed quality parameters were all analysed as a one-way ANOVA. Yield, protein, screenings, and Z30 DM were all analysed as a two-way ANOVA with cultivar and defoliation as factors.

In order to assess performance of winter wheats sown this early compared with the district practice of planting spring wheats later, ten DM cuts 1.2 m by 0.5 m were taken in the farmer's paddock surrounding the trial, which contained Kord wheat sown on 18 May 2013. These samples were threshed and grain weighed to determine grain yield.

Results

A wide range of seasons was experienced between 2009 and 2013 (Table 1). Woomelang in 2009 received average rainfall during the sowing period and winter, but lacked spring finishing rainfall. The 2010 season began well but delayed re-sowing from locust damage meant 6 weeks of growing-season time was lost. However, the spring rainfall was extremely favourable and enabled strong plant recovery after grazing. There was a wet summer fallow period before sowing in 2011, but the growing season was dry. In 2012, 56 mm of rain fell in late February and early March, providing the opportunity to sow winter wheat cultivars early at Birchip. Similarly, 2013 began with a 54 mm rainfall at Curyo in late February. Both 2012 and 2013 seasons received average rainfall.

Experiment 1

There were no differences in plant density between cultivars ($P = 0.578$), and mean plant density across all cultivars was 133 plants/m^2. There was a grazing × cultivar interaction for grain yield, protein and screenings (Table 2). Hindmarsh barley produced the highest yield for both grazed and ungrazed treatments, but also had the highest yield penalty (0.33 t/ha) from grazing. Grazing also reduced yield of the

Table 2. Grain yield and quality for grazed and ungrazed wheat and barley cultivars in Expt 1 at Woomelang in 2009
P-values and l.s.d.s are for the grazing × cultivar interaction, and bold values indicate significant effects of grazing in a cultivar

Cultivar	Grain yield (t/ha)		Protein (%)		Screenings (%)	
	Ungrazed	Grazed	Ungrazed	Grazed	Ungrazed	Grazed
			Barley			
Buloke	1.80	1.81	14.0	14.4	**2.5**	**5.8**
Hindmarsh	**2.38**	**2.05**	**13.6**	**14.5**	1.9	2.5
			Wheat			
Axe	**1.77**	**1.59**	13.2	12.6	3.5	4.2
Clearfield® Stiletto	1.45	1.50	14.9	14.4	**2.5**	**4.2**
Correll	1.86	1.73	**13.5**	**12.8**	**5.3**	**9.4**
Derrimut	1.90	1.82	12.5	12.5	5.5	5.8
Wyalkatchem	1.94	1.80	13.1	13.0	1.8	2.1
Yitpi	1.63	1.48	13.6	14.1	4.7	5.2
Young	**1.95**	**1.64**	12.7	12.6	**3.6**	**5.6**
P-value	0.047		0.009		<0.001	
l.s.d. (*P* = 0.05)	0.17		0.7		1.3	

very fast-maturing wheat cultivars Axe (0.18 t/ha) and Young (0.31 t/ha), but in the other five wheat and barley cultivars there was no significant effect of grazing on grain yield.

Differences in protein due to grazing were limited to Correll, in which there was no effect on yield, and Hindmarsh, where differences were related to dilution effects with increasing yield. Protein of all other varieties was unchanged by grazing. Grazing significantly increased screenings in four cultivars, which, in three cases (Correll, Buloke and Young), exceeded the commercial delivery standard (5%). As a main effect ($P < 0.001$), grazing increased screenings from 3.5% to 5%.

By the time of grazing at the 4-leaf stage, the barley cultivars had produced 25% more DM than the best wheat (Table 3). Of the wheat cultivars, Yitpi, Correll and Axe produced the most DM, but overall differences were small. Nutritional values were well in excess of those required for growing lambs or lactating ewes. Crude protein differed between cultivars, but neutral detergent fibre (mean 36%, $P = 0.192$) and metabolisable energy (mean 12.2 MJ/kg, $P = 0.109$) did not. Despite the low DM production, there was a useful amount of grazing available for the typically low stocking rates of the region, particularly in the barley cultivars.

Table 3. Nutritional value of different cultivars from dry matter cuts taken at growth stage Z14 before grazing on 23 June, for wheat and barley cultivars in Expt 1 at Woomelang in 2009

Cultivar	Z14 (23 June) dry matter (t/ha)	Crude protein (%)
	Barley	
Buloke	0.19	31.7
Hindmarsh	0.19	33.3
	Wheat	
Axe	0.14	29.8
Clearfield® Stiletto	0.10	32.4
Correll	0.14	30.3
Derrimut	0.10	31.1
Wyalkatchem	0.13	29.9
Yitpi	0.14	31.8
Young	0.09	30.6
P-value	<0.001	0.010
l.s.d. (*P* = 0.05)	0.04	1.9

Experiment 2

Plant density varied between cultivars ($P < 0.001$), with stands varying from 90 to 139 plants/m^2 (Table 4), and this had a significant effect on DM production when plants were grazed at Z13 (Fig. 1). Because of the late sowing of the experiment, DM at grazing was exceptionally low and provided very little feed (<0.1 t/ha).

Barley cultivars yielded on average 1.4 t/ha more grain than wheat. There was a near-significant grazing × cultivar interaction ($P = 0.06$), but this was largely driven by the response of Axe, in which grazing reduced yield by 0.4 t/ha. There was no effect of grazing in the other cultivars.

There was a near-significant ($P = 0.068$) increase in grain protein due to grazing of 0.6%, and an effect of cultivar, with Correll and Lincoln having lower protein than most other cultivars (Table 4). The generally low protein levels indicate that yields in the trial were probably N-limited, which is not surprising given the exceptionally favourable spring conditions in 2010 (111 mm rain in November).

There was a grazing × cultivar interaction on screenings, with most but not all cultivars recording an increase in screenings due to grazing. The main effect of grazing ($P = 0.006$) was to increase screenings by 0.6%, and for Yitpi the increase was significant (2.1%, Table 4).

Experiment 3

Emergence of Urambie and Hindmarsh was poor (42 and 60 plants/m^2, respectively), and this affected DM production at Z14. Plant density explained 99% of variation in DM at Z14 in the five barley cultivars (Fig. 2). When analysed with plant density as a covariate, there were no differences in DM at Z14 between cultivars. There was also no difference in DM at Z30

Table 4. Plant density, dry matter at Z13, grain yield and quality for wheat and barley cultivars in Expt 2 at Culgoa in 2010

Grain yield and grain protein are means of ungrazed and grazed values, and *P*-values and l.s.d.s are for the main effect of cultivar. For screenings, *P*-value and l.s.d. are for the grazing × cultivar interaction, and bold values indicate significant effects of grazing

Cultivar	Plant density (plants/m^2)	Dry matter at Z13 (5 July) (t/ha)	Grain yield (t/ha)	Grain protein (%)	Screenings (%) Ungrazed	Screenings (%) Grazed
			Barley			
Buloke	132	0.07	4.6	9.9	3.0	2.5
Gairdner	90	0.04	4.6	10.1	2.4	3.0
Hindmarsh	95	0.03	4.7	10.0	2.3	1.9
			Wheat			
Axe	112	0.06	3.4	10.1	2.5	3.1
Correll	112	0.05	3.4	9.5	4.5	5.3
Derrimut	116	0.03	3.2	9.9	4.4	5.4
Gladius	120	0.04	3.1	10.1	3.5	4.5
Lincoln	99	0.04	2.8	9.6	5.9	6.6
Yitpi	139	0.08	3.3	9.9	**5.5**	**7.6**
P-value	<0.001	<0.001	<0.001	0.003	0.021	
l.s.d. ($P=0.05$)	19	0.01	0.3	0.3	1.3	

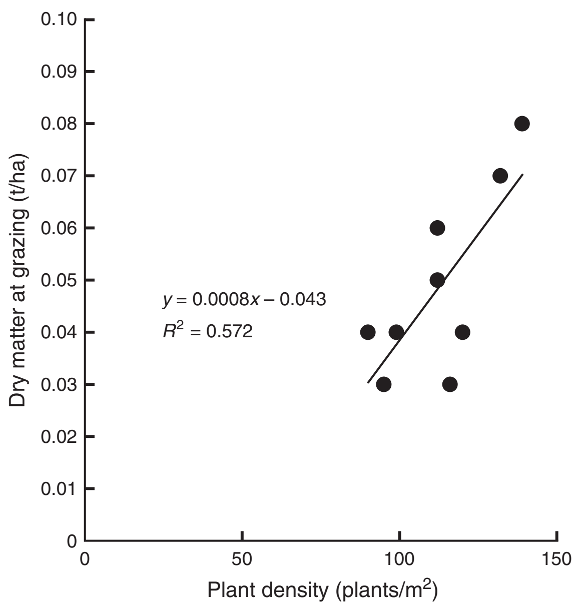

Fig. 1. Relationship between plant density and dry matter at grazing ($y=0.0008x-0.043$, $P=0.018$, variance accounted for 51%) for Expt 2 at Culgoa in 2010.

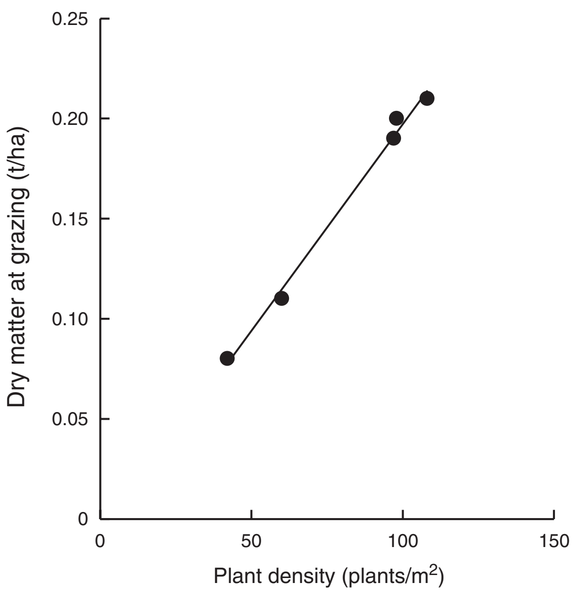

Fig. 2. Relationship between plant density and dry matter at Z14 in barley ($y=0.0021x-0.0092$, $P<0.001$, variance accounted for 99%) in Expt 3 at Corack in 2011.

between the two cultivars (Commander and Hindmarsh) selected for defoliation at Z30 (mean 0.43 t/ha, $P=0.915$).

In barley, there was no main effect of defoliation at Z14 ($P=0.143$) and no cultivar × defoliation interaction at Z14 ($P=0.845$) on grain yield. The main effect of cultivar was significant ($P<0.001$) and yields varied between 2.6 t/ha (Urambie) and 4.2 t/ha (Commander and Oxford). However, even when used as a covariate in analysis, plant density could explain 94% of variation in grain yield (Fig. 3).

In the two barley cultivars defoliated at Z30, there was no main effect of cultivar ($P=0.28$) and no defoliation × cultivar interaction ($P=0.959$) on grain yield. There was a near-significant ($P=0.059$) main effect of defoliation at Z30, which was to reduce yield by 0.4 t/ha relative to the undefoliated and Z14 treatments. There was no main effect of defoliation and no defoliation × cultivar interaction on screenings or protein. In cultivars defoliated at Z14, screenings only varied by cultivar (1.1–3.2%, $P<0.001$) and were all below delivery standard. There was a significant defoliation × cultivar interaction ($P=0.041$) on grain protein but effects were small (Table 5). Grain protein values indicate that yields were limited by N availability.

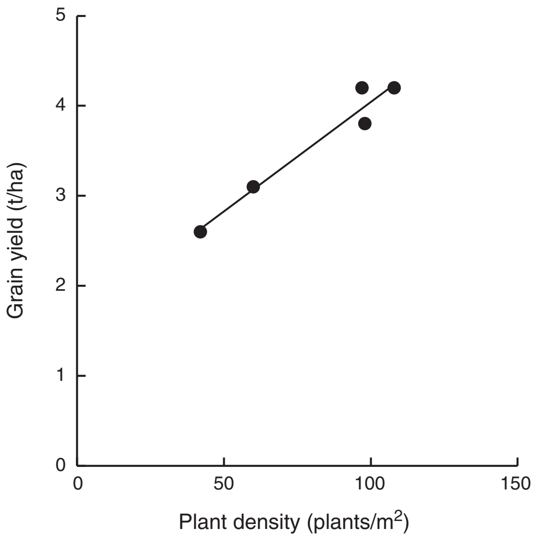

Fig. 3. Relationship between plant density and grain yield in barley ($y = 0.024x + 1.610$, $P = 0.004$, variance accounted for 94%) in Expt 3 at Corack in 2011.

Table 5. Grain protein (%) of barley cultivars either undefoliated or defoliated at Z14 for Expt 3 at Corack in 2011
P-value and l.s.d. are for the defoliation × cultivar interaction

Cultivar	Undefoliated	Defoliated at Z14
Buloke	10.8	9.9
Commander	9.7	9.3
Hindmarsh	9.9	10.7
Oxford	9	8.3
Urambie	10.3	9.9
P-value	0.041	
l.s.d. ($P = 0.05$)	1.2	

In barley cultivars defoliated at Z14 or Z30, there was no main effect of defoliation and no defoliation × cultivar interaction on either screenings or grain protein.

In wheat, Scout established at higher plant density than Axe (136 *v.* 116 plants/m^2, $P = 0.003$) and plant density was used as a covariate in all analyses. There was no difference in DM at Z14 (0.15 t/ha) or Z30 (0.36 t/ha) between cultivars.

There was no interaction between cultivar and defoliation, but grain yield was reduced from 2.6 t/ha (undefoliated) to 2.3 and 1.9 t/ha when defoliated at Z14 and Z30, respectively (Table 6). There was no significant effect of defoliation on grain protein, and contrary to the findings with wheat, defoliation increased screenings but not beyond delivery specifications (Table 6).

Experiment 4

Because of the very early sowing date, the spring wheat cultivars in this experiment were booting when the defoliation treatments were applied on 16 May, and defoliation killed main stems, which delayed anthesis by ~30 days. In addition, undefoliated spring wheats started flowering in late July, so both treatments were heavily frost-damaged, which was expressed in both reduced grain yield and high screenings from frost-damaged grain. The winter wheats flowered in mid–late September, which is considered optimal in this environment. At the time defoliation treatments were applied, Yitpi had accumulated more DM than the other cultivars (Table 7), reflecting its vigorous growth habit and high tolerance of the boron present at this site. There was a significant defoliation × cultivar interaction on grain yield, with defoliation increasing the yield of EGA Wedgetail by 0.6 t/ha and Forrest by 0.2 t/ha, with no effect observed in other cultivars (Table 7). From this early sowing date, the winter wheats yielded significantly more than the spring wheats. Yitpi in this trial yielded 1.9 t/ha, whereas in an adjacent trial sown at the customary time in early June, it yielded 2.5 t/ha (which was higher than the early-sown winter wheats at 2.1 t/ha), but when sown late June, only 1.6 t/ha. There was also a significant defoliation × cultivar interaction on screenings, with Bolac and Forrest having higher screenings than the winter wheats because of frost damage (Table 7). All treatments, except defoliated EGA Wedgetail, violated the screenings delivery standard limit of 5%.

Table 6. Grain yield and screenings for the two wheat cultivars undefoliated or defoliated at Z14 or Z30 in Expt 3 at Corack in 2011
Grain yield is the mean of undefoliated and defoliated treatments, and *P*-value and l.s.d. are for the main effect of defoliation. *P*-values and l.s.d.s for screenings data are for the cultivar × defoliation interaction

Defoliation	Grain yield (t/ha)	Screenings (%) Axe	Screenings (%) Scout
Undefoliated	2.6	2.6	3.7
Defoliated at Z14	2.3	2.6	4.7
Defoliated at Z30	1.9	3.3	4.6
P-value	<0.001	0.009	
l.s.d. ($P = 0.05$)	0.2	0.5	

There was a significant main effect of cultivar and defoliation on protein ($P = 0.043$), but this was due to the dilution effect and was inversely related to grain yield (data not shown).

Experiment 5

All cultivars established well when sown on 26 February, but no further rain fell until the end of May, and autumn was one of the warmest on record in the region. Consequently, plants were highly drought-stressed until the end of May, and defoliation was deferred until 9 July to allow plants to recover. Despite all cultivars having winter habit, there was considerable variation in development between cultivars when assessed on 12 September 2013 (Table 8). Revenue and the Chinese winter wheat YW443 were the last two cultivars to reach anthesis, and flowered at a time considered too late for reliable grain production in the Mallee. Cultivars that had not been defoliated were slightly more advanced than those that had, with the exception of Wylah, where defoliation seemed to accelerate development. Whistler, Wylah, EGA Wedgetail and Rosella all flowered in mid-September, which is optimal for yield potential in the southern Mallee.

At the time of defoliation (8 July), Wylah, Rosella and Revenue recorded the highest DM available to be defoliated (Table 9).

Table 7. Dry matter at defoliation on 16 May 2012, grain yield and screenings for different wheat cultivars in Expt 4 at Birchip in 2012

P-values and l.s.d.s are for the cultivar × defoliation interaction, and bold values indicate significant effects of defoliation

Cultivar	Dry matter, 16 May 2012 (t/ha)	Grain yield (t/ha)		Screenings (%)	
		Undefoliated	Defoliated	Undefoliated	Defoliated
Bolac	0.5	1.7	1.7	11.6	11.5
Forrest	0.6	**1.6**	**1.8**	**14.0**	**10.1**
Rosella	0.4	2.1	2.1	7.0	8.3
Wedgetail	0.4	**1.6**	**2.2**	5.1	4.6
Yitpi	0.8	1.9	1.9	8.7	7.5
P-value	0.002	0.003		0.012	
l.s.d. (*P* = 0.05)	0.2	0.2		2.0	

Table 8. Zadoks growth scale and development of different winter wheat cultivars on 12 September for Expt 5 at Curyo in 2013

Mid-September is the optimal anthesis period for wheat in the southern Mallee

Cultivar	Undefoliated		Defoliated	
	Zadoks stage	Growth stage	Zadoks stage	Growth stage
Revenue	39	Flag leaf emerged	33	Three nodes on main stem
Rosella	60	Early anthesis	51	Early heading
Wedgetail	66	Mid anthesis	61	Early anthesis
Whistler	63	Early anthesis	51	Early heading
Wylah	61	Early anthesis	64	Mid anthesis
YW443	46	Booting	39	Flag leaf emerged

Table 9. Dry matter production on 8 July, undefoliated grain yield and protein of winter wheat cultivars in Expt 5 at Curyo in 2013

P-values and l.s.d.s are for the main effect of cultivar

Cultivar	Dry matter 8 July (t/ha)	Grain yield (t/ha)	Protein (%)
Revenue	0.5	3.4	11.5
Rosella	0.4	3.3	12.2
Wedgetail	0.3	2.8	12.4
Whistler	0.3	3.0	11.8
Wylah	0.4	2.8	13.1
YW443	0.4	1.7	15.4
P-value	<0.001	<0.001	<0.001
l.s.d. (*P* = 0.05)	0.1	0.3	0.9

There was no significant cultivar × defoliation interaction ($P = 0.272$), whereas defoliation, on average, reduced grain yields by 0.3 t/ha ($P < 0.001$) compared with undefoliated treatments. Grain yields of winter wheats (except Revenue at 3.4 t/ha and Rosella at 3.3 t/ha; Table 9) were less than of spring wheat cv. Kord sown on 18 May in the farmer's paddock surrounding the trial (mean 3.6 t/ha, range 3.0–4.4 t/ha).

All cultivars achieved the protein and screenings specifications required to meet their maximum quality segregation. Protein increased when cultivars were defoliated (average 0.3%), but this was in proportion to the lower grain yield (Table 9).

Discussion

This study found very levels of DM production for grazing in spring (0.03–0.21 t/ha) and winter (0.4–0.5 t/ha) cultivars similar to those simulated by Moore (2009) for the region. Such levels are certainly useful for sustaining animals during the winter feed-gap; however, feed on-offer is strongly affected by sowing date and plant density (Bell *et al*. 2015).These experiments also reinforce the point made by Harrison *et al*. (2011) that the grain yield response to grazing or defoliation in spring and winter cereals is highly variable. This variability was observed despite the fact that grazing and defoliation treatments were applied during the supposedly 'safe' grazing window (before Z30) developed for spring cereals (Dove and Kirkegaard 2014). This corroborates the findings of Latta (2015), who investigated defoliation of spring cereals in a similarly low-rainfall Mediterranean climate.

The majority of yield responses in this set of experiments were either neutral (six cultivars in Expt 1, Expt 2, barley in Expt 3 and three cultivars in Expt 4) or negative (three cultivars in Expt 1, wheat in Expt 3 and all cultivars in Expt 5), which seemed to result from interactions between genotype and numerous site-specific environmental and management factors, making it difficult to predict frequency and magnitude of yield responses. In this set of experiments the only recorded yield increase due to defoliation was in Expt 4, where defoliation increased yield of EGA Wedgetail and Forrest by 0.6 and 0.2 t/ha, respectively. Neutral responses to defoliation occurred in the two experiments (Expts 2 and 3) where yield was probably limited by N availability. Interestingly, this suggests that yield penalties from defoliation may not occur as frequently in farmer's paddocks, which are frequently limited by N (Hochman *et al*. 2009; Hochman *et al*. 2012), as they do in small plot experiments where N is generally added so that it is non-limiting.

Although the variable genotype × management response to defoliation is intriguing from an agronomic and physiological perspective, the lack of predictability is a significant barrier to adoption of dual-purpose cereals on Mallee farms, where grain yield is a primary determinant of profitability. The relatively small amounts of grazing possible from the currently grown spring cultivars will rarely be able to offset even small reductions in yield, which this set of experiments indicates are a likely outcome from defoliation before Z30. Three out of five experiments recorded an increase in levels of screenings, which is a significant further deterrent because it reduces grain price and in some cases makes it locally unsaleable. If future research were to elucidate the physiological mechanisms underpinning yield and grain-size responses to defoliation such that by careful selection of genotype and management they could largely be avoided, greater adoption would be likely.

In all experiments comparing barley and wheat, barley consistently produced more biomass at the time of grazing or defoliation than wheat, consistent with observations made by Dove *et al*. (2012), among others. In Expt 3, grazing at Z14 and Z30 reduced yield of wheat, but only Z30 grazing reduced yield of barley. This suggests that barley may have greater promise than wheat for dual-purpose use in this region, but is still prone to variable responses in yield and quality. Barley also has a lower grain price, which makes a balance between value of grazing and the income lost from grain yield penalty more likely.

Experiments 4 and 5 demonstrated that winter wheats sown earlier in the year tend to produce much more forage than the spring wheats commonly grown in the Mallee, which are suited to growing only from late April onward. Winter wheats can be sown much earlier than spring wheats but still flower at a time optimal for yield, and because of their vernalisation requirement, winter wheats are slower to reach Z30 and hence remain in the 'safe' grazing window for longer. Both of these experiments validate the simulation studies of Moore (2009), who found that winter wheats were, on average, able to produce significantly more forage than spring wheats. They also support the simulated study of Bell *et al.* (2015) for the high-rainfall zone of Australia, and the assertions of Radcliffe *et al*. (2012) that dual-purpose cereals must have a winter habit. Moore (2009) and Bell *et al*. (2015) also found that winter wheats sown early were able to yield more than spring wheats sown later. This is intriguing given the overwhelming emphasis that has been placed on breeding fast-maturing spring wheats for the region. Although our experiments did not include direct comparisons of winter wheats sown early with spring wheats sown later, results that can be inferred from using neighbouring trials (Expt 4) and surrounding farmer paddocks (Expt 5) as a point of comparison indicate that the best performing winter wheats used in these trials are able to yield as well as, or perhaps slightly less than, faster spring wheats sown later. The winter lines are also at a comparative disadvantage to spring lines, in that most of them were released more than a decade ago; the winter cultivar Rosella, which performed well in both Expts 4 and 5, was released in 1985. Given the genetic yield gain for a similar environment quantified by Sadras and Lawson (2011), this puts it at a 0.7 t/ha yield disadvantage to the most recently released spring wheats. The winter wheats used in this study also lack tolerance of many of the soil constraints endemic to alkaline soils (e.g. cereal cyst nematode, boron, salinity and aluminium), which as demonstrated by McDonald *et al*. (2012) are very important in determining local adaptation and yield performance of cultivars in southern Australia. Boron levels at Culgoa were high, and it is known that most of the winter wheats released by the now-defunct Wagga Wagga Agricultural Research Institute breeding program (Rosella, Wylah, Whistler, EGA Wedgetail) are intolerant of boron (Peter Martin, breeder; pers. comm.). In Expt 5, the yield of Revenue (3.4 t/ha) was particularly impressive considering how late it flowered, but maintenance of yield at late flowering dates was a key selection criterion in the breeding program that produced this cultivar (Sue Klevin, breeder; pers. comm.).

Significant production gains for both livestock and cropping enterprises could likely be achieved if breeding effort were to focus on adapting winter wheat and barley cultivars to the Mallee environment. Recent advances in identification of molecular markers for major vernalisation alleles (Eagles *et al*. 2009, 2010) opens the possibility to generate winter wheats by crossing many of the highly adapted spring wheats used in this study (e.g. Derrimut/Wyalkatchem) and selecting winter progeny through either phenotyping or molecular marker techniques. It would also finally realise a long overdue prediction made by Simmonds (1989):

'In 1983, the [Wagga Wagga Agricultural Research] Institute released two winter cultivars, Osprey and Quarrion. These are the first wheats to offer Australian growers the advantage of grazing their livestock on the crop during its winter vegetative stage, without significant effect on subsequent grain yield. The majority of Australia's future wheats are expected to be bred for this characteristic.'

Acknowledgments

We are grateful for the funding support from the Mallee Catchment Management Authority (2009), GRDC and Caring for Our Country project BWD00018 'Grain & Graze 2' (2010, 2011, 2012 and 2013), and BCG membership and GRDC projects CPS00111 'Identifying farm scale opportunities to improve WUE: A nationally coordinated systems approach' (2012) and CSP00178 'Increasing yield and reducing risk through early sowing in the southern grains region' (2013). The provision of land for trials at Woomelang by Chris and Janice Kelly, Culgoa by Peter and Marg Shirley, Corack by the Reilly family, Birchip by the Barber family, and Curyo by Peter and Brenda Doran is gratefully acknowledged. We also thank BCG technical staff for assistance with experimental management and measurements.

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