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An evaluation of the growth and yield of perennial cereals in two contrasting environments

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ABSTRACT

Perennial cereals have been proposed as an alternative to annual crops in Australian mixed grazing and cropping enterprises. However, there is a lack of data defining suitable regions, and which species may be successfully grown as dual-,purpose grain and fodder crops. This research compared the growth of three candidate perennial cereals, intermediate wheatgrass, mountain rye, and hybrid perennial wheat, to a forage species (tall wheatgrass) and an annual winter wheat. The crops were grown in two contrasting Australian cropping and livestock regions, Cowra in NSW (temperate) and Pittsworth, Queensland (sub-tropical). In year 1 treatments included early, late, and early plus late defoliation, to simulate grazing before reproductive development. Phenology was recorded monthly and the crops harvested each year as the plants reached grain maturity. At Pittsworth defoliation treatments produced no significant effect on yields in year 1. At Cowra, the undefoliated treatments produced the highest biomass and grain yields. Intermediate wheatgrass yield was very low in year 2 at Pittsworth with temperatures > 35°C occurring during early reproductive development. Mountain Rye had slightly higher grain yields, but had longer maturity compared to the annual and hybrid perennial wheat. It was concluded that the longer maturity times of mountain rye and intermediate wheatgrass made them vulnerable to reproductive stage heat and moisture stress, especially at Pittsworth.

1. Introduction

Mixed farming systems that integrate grazing and cropping enterprises are common across southern Australia (Bell and Moore, 2012; McGrath et al., 2021). These systems typically combine annual cereal crops with legume and pasture phases. However, there is increasing concern that grain production from annual crops, with associated soil degradation risks, is not sustainable (Chapman et al., 2022; Crews et al., 2016). It has been proposed that integrating perennial grain crops into compatible farming enterprises may address the environmental risks associated with annual cropping systems while maintaining food security (Crews et al., 2018; Duchene et al., 2020). A range of perennial grains, potentially suitable for integration in Australian farming systems, have previously been evaluated in Australia (Hayes et al., 2012, 2017a; Larkin et al., 2014). Although the wheat x wheatgrass derivatives showed promising potential in dual-purpose grain and graze systems (Newell et al., 2020) with grain attributes that were suitable for multiple end-uses (Newell et al., 2021; Pleming et al., 2023), they lack the long-term persistence to be deployed as a true perennial grain (Hayes et al., 2012, 2018). This is thought to be associated with aftermath heading and the apparent inability of the wheat x wheatgrass derivatives to return to a vegetative growth stage following harvest (Larkin et al., 2014).

An alternative approach to improve the persistence of perennial grains is to select for improved grain attributes in suitable perennial grass species. Intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey) is an example where development as a perennial crop is most advanced, with grain incorporated in food products under the trade name Kernza® (Bajgain et al., 2022). However, the performance of perennial grains based on this species is uncertain at lower latitudes (i.e., closer to the equator) environments, due to the high vernalization and daylength requirements of this species (Locatelli et al., 2022). In a global evaluation of perennial cereals in contrasting environments, material derived from tall wheatgrass (*Thinopyrum ponticum*

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(Podp.) Barkworth & D.R.Dewey) was found to be better adapted to lower latitude environments than intermediate wheatgrass (Hayes et al., 2018).

Mountain rye (*Secale strictum* (C. Presl) C.Presl, syn. *S. montanum*) is a forage cereal species that has recently been investigated as a candidate perennial crop. It has shown a range of desirable grain quality attributes for a diversity of end uses (Newell, 2021). Although tall wheatgrass, intermediate wheatgrass, and mountain rye are known to be useful as forage plants (Barriball, 2020; Clements et al., 2003; Freer et al., 1997; Harmoney, 2005; Newell and Hayes, 2023), the grain production potential of these species in low-latitude, winter grain production environments has been less well studied. Mountain rye, similar to intermediate wheatgrass, is a cool climate species and is assumed to also have high vernalisation requirements. Cool climate grasses have generally evolved so that reproductive progression occurs after a period of chilling, followed by an increased number of daylight hours (Chouard, 1960; Heide, 1994). At lower latitudes there is a risk that the later occurrence of the requisite daylength may be accompanied by damaging higher temperatures (Farooq et al., 2011; Ivancic et al., 2021) exacerbated by possible moisture stress (Innes et al., 2015). Therefore, it is important to understand the environmental limitations and management requirements of perennial cereals such as intermediate wheatgrass and mountain rye, if they are to be integrated into current farming systems. A comparative study, which includes a commonly grown annual wheat, was considered a means of gauging the growth and grain production potential of candidate perennial cereal species in two lower latitude environments.

Perennial cereals have the potential to produce livestock forage as well as grain (Newell and Hayes, 2017). Bell et al. (2010) analysed the characteristics of perennial cereals that could potentially make them advantageous for Australian farmers and how they could be integrated into Australian farming systems. They concluded that for financial benefit there needs to be a grain yield of at least 40 % of current annual wheat yields, along with larger proportions of cropping land being allocated to pasture production. Experimental defoliation treatments have been used to simulate livestock grazing of perennial cereals (Favre et al., 2019; Hunter et al., 2020a; Newell and Hayes, 2017) and the subsequent effects on biomass and grains yields (Hunter et al., 2020a; Hunter et al., 2020b; Newell and Hayes, 2017; Pugliese et al., 2019; Puka-Beals et al., 2022). Defoliation has been found to increase total biomass production (Pugliese et al., 2019), but this depends on the timing of the defoliations (Hunter et al., 2020a) and the number of defoliations (Puka-Beals et al., 2022).

The aims of this study were to compare the growth and yields of selected perennial grain species with an annual wheat in field plots at two low latitude environments (Cowra, NSW (temperate) and Pittsworth, Queensland (sub-tropical)) in Australia. Additionally, a comparison was to be made of the effects of four defoliation regimes (none, early, late, and early plus late) on the biomass and grain yields of each species. The first hypothesis to be tested was that the cooler climate species, intermediate wheatgrass and mountain rye, would have relatively lower grain production (compared to wheat) at Pittsworth than at Cowra, while hybrid perennial wheat would have similar yields relative to wheat at both locations. The second hypothesis was that an increased defoliation frequency would increase total biomass production at both locations.

2. Methods

2.1. Germplasm

The field experiments included two perennial grasses, intermediate wheatgrass (IWG) and mountain rye (MR) which are both candidates for domestication as perennial grain crops. The IWG germplasm was previously evaluated in Australia as an early breeding line in the development of Kernza (Hayes et al., 2012; Larkin et al., 2014), originating from the Land Institute (Salina, KS) in 2009, previously designated as breeder code IWG 3182. More recent Kernza lines could not be included due to their lack of availability and the lengthy process of importing new germplasm into Australia (Larkin et al., 2014). The mountain rye used has shown promise as a forage grass (Oram, 1996) with grain properties suitable for diverse uses (Newell et al., 2021). A perennial wheat breeding line 11955 (HPW: described as PI 550713 in Cox et al. 2006) developed from a cross between *Triticum aestivum x Th. ponticum* was also included. These perennial grains were compared to a commonly grown dual purpose annual winter wheat cultivar "EGA_Wedgetail" (AW: *T. aestivum* L) along with the perennial forage species, tall wheatgrass cv. Dundas (TWG: T*h. ponticum* (Podp.) Barkworth & D.R. Dewey).

2.2. Site description

Experiment 1 was established in 2022 at the NSW Department of Primary Industries & Regional Development Cowra Agricultural Research Advisory Station, Australia, on a Red Chromosol soil (Isbell, 2016) (latitude −33.8, longitude148.7). Experiment 2 was also established in 2022 near Pittsworth in south-east Queensland, Australia, on a Grey Vertosol soil (Isbell, 2016) (latitude −27.79, longitude 151.58). The Cowra site (Table 1) is a temperate environment and is generally a cooler climate than the subtropical site at Pittsworth (Table 2). Cowra has an even rainfall distribution throughout the year, while Pittsworth, located closer to the tropics, has a more pronounced summer rainfall pattern. In Cowra the winter temperatures regularly drop below 5°C. Pittsworth has warmer winter temperatures, however, temperatures below 5°C are recorded between June and August. Generally, at Pittsworth the night-time temperatures are warmer and there are fewer potential frost days (31) than at Cowra (62) (Australian Bureau of Meteorology, 2025).

Prior to sowing, three 20 mm (Pittsworth) and 42 mm (Cowra) diameter core samples were taken to a depth of 1.0 m. Each core was orientated within the middle of each replicate in the experiment. Each core was divided into 10 cm sections from the surface down to 0–0.4 m depth and in 20 cm sections from 0.4m-1m depth. Soils were dried at 40 °C until a constant weight was reached, Dry soil was then ground to pass through a 20 mm sieve, with each depth section bulked across the three sample cores for chemical analysis. Cowra samples were sent to the AgEnviro Laboratory (ISO 14173 (NATA), Wollongbar, Aus.) and Pittsworth samples to the CSBP Soil and Plant Analysis Laboratory (Bibra Lake WA 6163) to determine mineral nitrogen (NO3 & NH4, via KCl extraction), pH (1:5 CaCl suspension), available phosphorus (Colwell), and total soil organic carbon (Dumas combustion, following acid pretreatment) (Table 3). All procedures were based on protocols as set out in (Rayment and Lyons, 2010). In mid-July at each site (a week since any significant rainfall event) a single soil core from the centre of the experimental site was also taken to a depth of 1 m to determine the upper drained upper limit moisture content. The soil core was divided into 10 cm sections. Each section was weighed and dried at 105°C for 5 days for the determination of bulk density and gravimetric moisture content (Table 4).

2.3. Design

Each experiment was a randomised complete block design with each block containing one of each species by defoliation combination. On the 18th of May 2022, the five species were sown at Cowra, replicated four times, amounting to 80 plots. Fertiliser (NPK:25–5–8.8) was applied at the rate of 75 kg/ha. On the 20th of June 2022 four species were sown at Pittsworth, with four replicates, giving a total of 64 plots (TWG was omitted at Pittsworth). The Pittsworth site received 100 kg/ha of urea and 100 kg/ha of a compound fertliser CK88 (NPK:15–4.4–11.5). At both sites, plots were 100 cm by 30 cm and contained three rows 15 cm apart. Seeds were sown by hand with the aid of a steel template that

Table 1
Cowra, NSW, AUS climate monthly averages for years 1985–2023 (Australian Bureau of Meteorology, 2025). Max.T is the maximum average temperature, Min.T is the minimum average temperature.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Rain (mm)	47	53	50	41	38	48	51	49	49	51	62	57
Max.T (°C)	32.5	31.5	28	24	18.5	15	14	15.5	23	23.5	27	30
Min.T (°C)	16.5	16	13.5	9	6	4	3	3	5	8	11.5	14

Table 2
Pittsworth, Qld, AUS climate monthly averages for years 1985–2023 (Australian Bureau of Meteorology, 2025). Max.T is the maximum average temperature, Min.T is the minimum average temperature.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Rain (mm)	80	81	72	33	46	32	28	27	29	64	84	100
Max.T (°C)	30.5	29.5	28	25	21	18	18	19.5	23	26	28	29.5
Min.T (°C)	17.5	17	15.5	12	8	5	3.5	4.5	7.5	11.5	14	16

Table 3
Soil chemical properties at Cowra, NSW, AUS and Pittsworth, Qld, AUS taken at sowing in 2022. NH3-N = ammonia nitrogen, NO3-N = nitrate nitrogen, P = phosphorous, K=potassium, OC=organic carbon.

	Cowra						*Pittsworth*					
Depth	***NH3-N***	***NO3-N***	***P***	***K***	***OC***	***pH***	***NH3-N***	***NO3-N***	***P***	***K***	***OC***	***pH***
cm	***mg/kg***	***mg/kg***	***mg/kg***	***mg/kg***	***%***	***$CaCl_2$***	***mg/kg***	***mg/kg***	***mg/kg***	***mg/kg***	***%***	***$CaCl_2$***
0–10	3	3.8	38	347	0.86	5.1	9	11	17	305	1.47	6.7
10–20	1.7	3.4	9	144	0.39	4.9	11	17	11	250	1.43	7.4
20–30	1.1	6	4	78	0.26	5.2	13	21	10	235	1.37	7.5
30–40	0.73	5.1	3.3	55	<0.2	5.6	10	22	10	237	1.17	7.8
40–60	0.54	5	4.3	39	<0.2	6.1	12	22	6	205	1.27	7.7
60–80	0.55	4.5	5.2	51	<0.2	6.8	11	23	5	208	1.17	7.9
80–100	0.71	3.2	3.6	86	<0.2	7.3	8	22	7	211	0.83	7.8

Table 4
Bulk density and drained upper limit of soils at Cowra, NSW, AUS and Pittsworth, Qld, AUS.

	Cowra			*Pittsworth*		
Depth cm	***Bulk density g/cm^3***	***Gravimetric moisture g/g***	***Volumetric moisture cm^3/cm^3***	***Bulk density g/cm^3***	***Gravimetric moisture g/g***	***Volumetric moisture cm^3/cm^3***
0–10	1.59	0.13	0.21	1.00	0.26	0.26
10–20	1.72	0.12	0.20	1.02	0.24	0.25
20–30	1.75	0.12	0.21	1.04	0.25	0.26
30–40	1.71	0.12	0.21	1.07	0.26	0.27
40–50	*			1.09	0.26	0.28
50–60	1.78	0.12	0.22	1.11	0.26	0.29
70–80	1.80	0.12	0.22	1.13	0.26	0.29
80–90	1.86	0.13	0.23	1.16	0.26	0.30
90–100	1.91	0.14	0.26	1.18	0.25	0.29

* Cowra 40–50 cm – no bulk density determination due to the high gravel content of this layer.

made indentations 2 cm deep and 10 cm apart in each sowing row. Three seeds were sown in each indentation in each row. When plants had developed to the first leaf stage, the middle and buffer rows were thinned to one plant per indentation. If necessary, excess plants were transplanted so each row had ten plants. Due to establishment challenges associated with surface crusting, some buffer rows (e.g. HPW and MR at Pittsworth) had less than 10 plants. The AW was resown in year 2 on the 24th of April 2023 at Pittsworth and the 5th of May at Cowra.

2.4. Management

Overhead irrigation was used, as necessary, for germination and plant establishment, after which plots were rainfed. At Cowra, 300 ml/ha Prosaro (Prothioconazole 210 g/L) was applied on the 20th September 2022, to protect against leaf diseases. Tebuconazole fungicide (430 g/L) was applied at 290 ml/ha to the experiment at Pittsworth on the 15th October 2022 to control stripe rust (*Puccinia striiformis* f.sp. *tritici*). Fencing was required at both sites to exclude rabbits and kangaroos. Mouse bait (zinc phosphide 50 g/kg) was spread at both sites when rodent damage was evident.

2.5. Defoliation and harvest methods

To simulate the effects of grazing, or harvesting biomass for fodder, there were three defoliation treatments: an early defoliation (equivalent to initial grazeable biomass), a late defoliation before any species reached reproductive stage (Zadoks stage 31 (Zadoks et al., 1974)), and an early plus a late defoliation. All species received the early or late defoliation treatment on the same day at each location, to simulate the effects of either grazing or harvesting a paddock containing a mixture of these species. At the first defoliation, most plants were at the 2–3 leaf stage, and at the second defoliation plants were at the 5–7 leaf stage. When a plot was defoliated all rows were cut (using a handheld sickle) to 10 cm height and the middle row used to determine yield. Early and late defoliations were done on the 2nd and 26th of August 2022 respectively, at Cowra. At Pittsworth defoliations were undertaken on the 29th of August and the 25th of September 2022. The final biomass and grain harvest of each species (Table 5) was completed when most of the heads were judged to be ripe, when the peduncle colour had changed from a green to a straw yellow (Zadoks stage >90). Only the centre rows were used for determination of yield components. The biomass recorded for year 1 are the total biomass from the defoliations and final harvest of each species. There were no defoliations in year 2, the biomass recorded for year 2 was the total from the final harvest.

2.6. Data collection

At approximately four weekly intervals during year 1 each plot was assessed for phenological development (Zadoks et al., 1974). The three middle plants of the centre row of each plot were measured for height, number of tillers, number of mainstem leaves, growth stage, and surviving plant numbers. Pest and diseases were noted at each stage. Samples from diseased plant occurrences were sent for testing to identify the pathogens (EMAI, Plant Health Diagnostic Services. ISO 14495. Menangle, AUS).

Prior to each grain harvest, the centre row head and tiller numbers were recorded. After the year 1 harvest the biomass from each plot was separated into components (stems, leaves, and heads). In year 2, only heads were separated from the harvested biomass. After each harvest all components were dried and weighed, the heads threshed in a stationary thresher (Kimseed, Wangara, WA), and the cleaned grain weighed for each plot. From the cleaned grain a sample of 100 grains was weighed and the thousand kernel weight (TKW) calculated. Biomass was recorded as the total weight of the dried stems, leaves and heads in year 1, including the biomass from defoliation. There were no defoliations in year 2 (partly due to plant mortality and the corresponding lack of biomass to defoliate in many cases), so the year 2 biomass was recorded as the total weight of the final harvested material.

2.7. Data analysis

The impact of species and defoliation treatment on yields (biomass and grain) and survival, were analysed as a two-way ANOVA with the R programming language version 4.3.1 (R-Core-Team, 2021). The ANOVA assumptions of normality were checked visually by plotting the residuals. When ANOVA identified an effect at $P \leq 0.05$, Fishers LSD (95 % confidence level) was used to separate the means. Location was not included in the ANOVA analysis as a) it was not replicated or randomised, and b) there were a different number of species at each location. At each location the percentage yield (biomass and grain) of each species compared to annual wheat were calculated. The interacting effects of the input variables (year, species, and defoliation) on the output variables (total biomass, grain yield, thousand kernel weight, and plant persistence) were analysed by ANOVA for significance. The effect of species on persistence was also analysed by ANOVA at each location. Graphical analysis of phenology timing was produced using the *ggscatter()* function from the R programming language 'ggpubr' package. As there were no defoliations done in year 2, the phenology analysis was only done for the no-defoliation groups, so that year 1 and year 2 treatments used for the analysis were identical. Each point plotted was the mean of the four replicates of each species, with error bars indicating the standard error of the mean.

Table 5
Harvest dates at Cowra, NSW, AUS and Pittsworth, Qld, AUS for Hybrid Perennial wheat (HPW), Mountain Rye (MR),Annual Wheat (AW), Intermediate Wheatgrass (IWG), and Tall Wheatgrass (TWG).

	Cowra		*Pittsworth*	
Species	*Year 1*	*Year 2*	*Year 1*	*Year 2*
HPW	13th Jan 2023	-*	4th Jan 2023	3rd Oct 2023
MR	24th Jan 2023	12th Jan 2024	6th Feb 2023	6th Feb 2023
AW	9th Dec 2022	17th Nov 2023	3rd Dec 2022	16th Oct 2023
IWG	3rd Feb 2023	7th Feb 2024	24th Apr 2023	4Mar 2024
TWG	23 Feb 2023	4th Mar 2024	na†	na†

* negligible survival, †not sown at this site.

3. Results

3.1. Phenology – growth stage timing

Compared to year 1, cool minimum temperatures (important for vernalisation) persisted further into year 2 at both Cowra and Pittsworth (Fig. 1). Higher maximum temperatures were experienced earlier at both locations in year 2, combined with a reduced spring and summer (September-February) rainfall. Daylengths (important for reproductive induction) reached 13 h on the 13th of October in Cowra and on the 25th of October in Pittsworth (Fig. 1).

The fastest phenology progression was observed in AW (Fig. 2) at both Cowra and Pittsworth with AW reaching flowering stage (Zadoks > 50) by mid-October. The next fastest maturing line was HPW, flowering in late October (Cowra) and early November (Pittsworth). In year 1, MR flowered in mid-November (Cowra) and early December (Pittsworth), while IWG flowered in mid-December (Cowra) and late December (Pittsworth). In year 2 at Pittsworth, the MR died before reaching reproductive development, and the IWG remained vegetative. At Cowra in year 1, TWG was the slowest to reach grain maturity, approximately three weeks after IWG.

3.2. Disease occurrence

Yellowing of herbage was observed at Cowra (Fig. 3). Test results indicated a mixture of crown rot, pythium, and some parasitic nematodes. The worst affected perennial species were the IWG and HPW. The least affected species was the MR. The disease effects are reflected in the low survival rates of IWG and HPW at Cowra relative to Pittsworth (Table 11). Minor yellowing of leaf tissue was observed at Pittsworth, mostly associated with stripe rust.

3.3. Cowra ANOVA P-values

At Cowra, the species type had a significant ($P < 0.01$) effect on all dependent variables (Table 6). The year (year 1, year 2), and the interaction between the year and species, significantly ($P < 0.01$) affected all dependent variables, apart from TKW. Defoliation had significant effects on total biomass ($P = 0.03$) and grain yield ($P = 0.01$).

3.4. Pittsworth ANOVA P-values

At Pittsworth, year, species type, and the interaction of year and species had a significant ($P < 0.01$ and $P = 0.01$) effect on all dependent variables (Table 7). Defoliation had no significant effects on any of the dependent variables.

3.5. Biomass, grain yields, and seed size

In all species grain weights were lower in year 2 compared to year 1 (Table 8). At Pittsworth this can be partially explained by the hotter and drier conditions in year 2 compared to year 1 (Fig. 1). Seed sizes (TKW) were significantly higher for AW and HPW compared to MR and IWG at both locations in year 1 and year 2, apart from year 2 at Pittsworth.

3.6. Species effects

Less than 50 % of the IWG plots at Pittsworth proceeded to grain development in year 1, and none in year 2 (Table 8). At Cowra, the

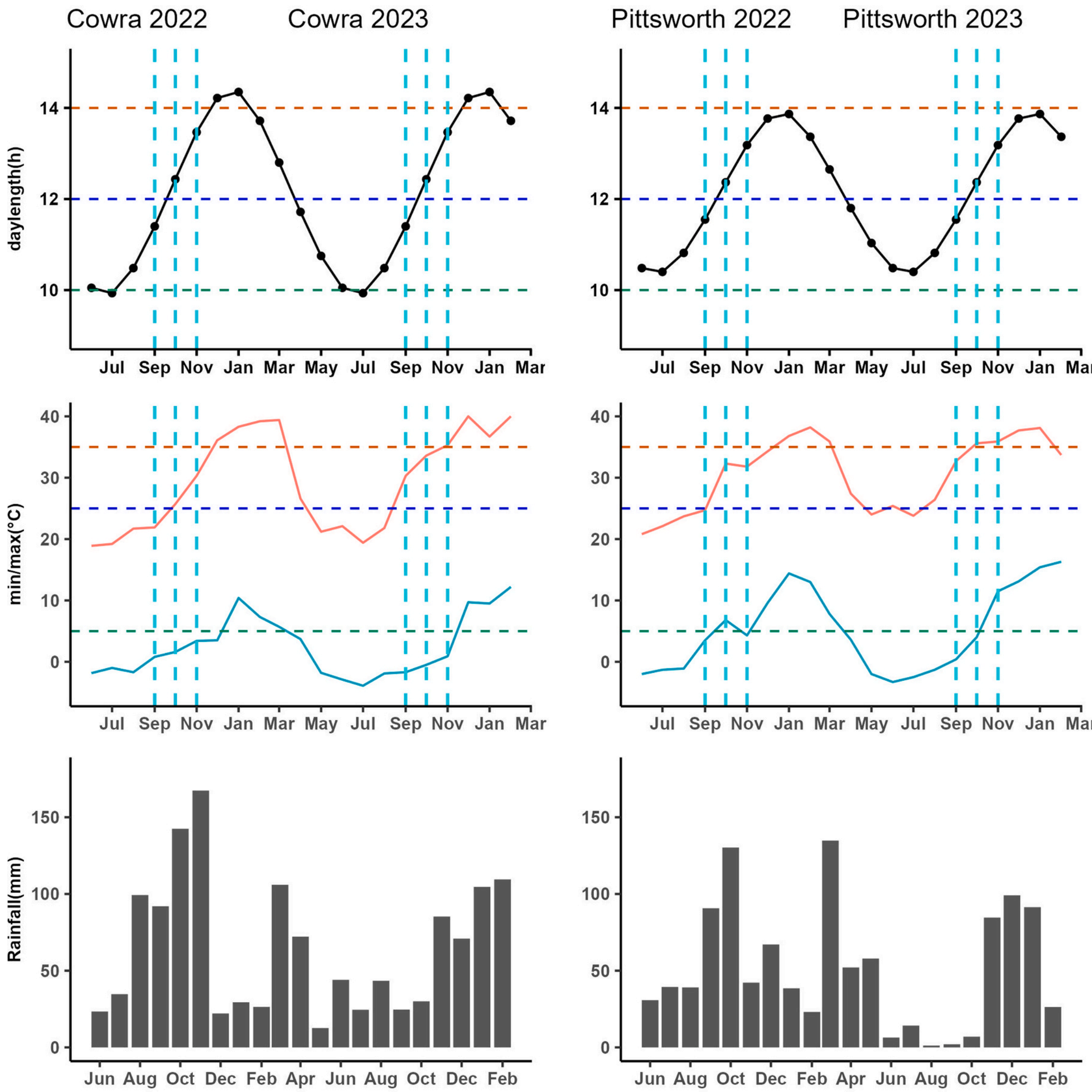

Fig. 1. The panels show the daylengths, minimum and maximum temperatures, and monthly rainfall recorded over the 2022 and 2023 growing seasons at Cowra, NSW, AUS and Pittsworth, Qld, AUS. The lower green line for min/max marks 5°C, the blue 25°C, and the orange 35°C. The vertical bars are reference marks for the months of September, October, and November.

disease impacts on HPW and IWG in year 1 resulted in very few plants persisting to produce grain in year 2 (Table 11). Biomass weights varied between locations, but MR had the highest and second highest biomass production in year 1 at Cowra and Pittsworth respectively. The thousand kernel weight (TKW) relationship between species remained consistent between years, with AW having the highest TKW and IWG the lowest TKW, apart from Pittsworth in year 2, where the TKW of HPW was slightly higher than AW.

3.7. Yields compared to wheat

At Pittsworth, the two year total biomass yields of HPW, MR, and IWG were higher (353 %, 209 %, and 108 %) than AW (Table 9). The grain yields of MR and IWG at Pittsworth were lower (33 % and 0 %) than AW. At Cowra the grain yields of MR and IWG were 165 % and 10 % of the AW grain yield. The IWG at Cowra was affected by disease which may have reduced the Cowra IWG grain yield. Both the two year total biomass and grain yields of HPW were considerably higher (353 % and 199 % relative to AW) at Pittsworth than they were at Cowra (48 % and 15 %) (Table 9).

3.8. Defoliation effects

The early defoliations (at 10 cm height) produced negligible biomass in many plots in year 1. Across all species, the only significant effects of defoliation in year 1 were observed at Cowra (Table 10), with highest biomass and grain weights in the no-defoliation treatment group. The defoliations shown are for year 1 (there were no defoliations in year 2).

3.9. Plant persistence

The persistence of MR was similar across locations (Table 11). Both the HPW and IWG had superior persistence at Pittsworth compared to Cowra.

4. Discussion

The HPW performed well in Pittsworth, exceeding both the biomass

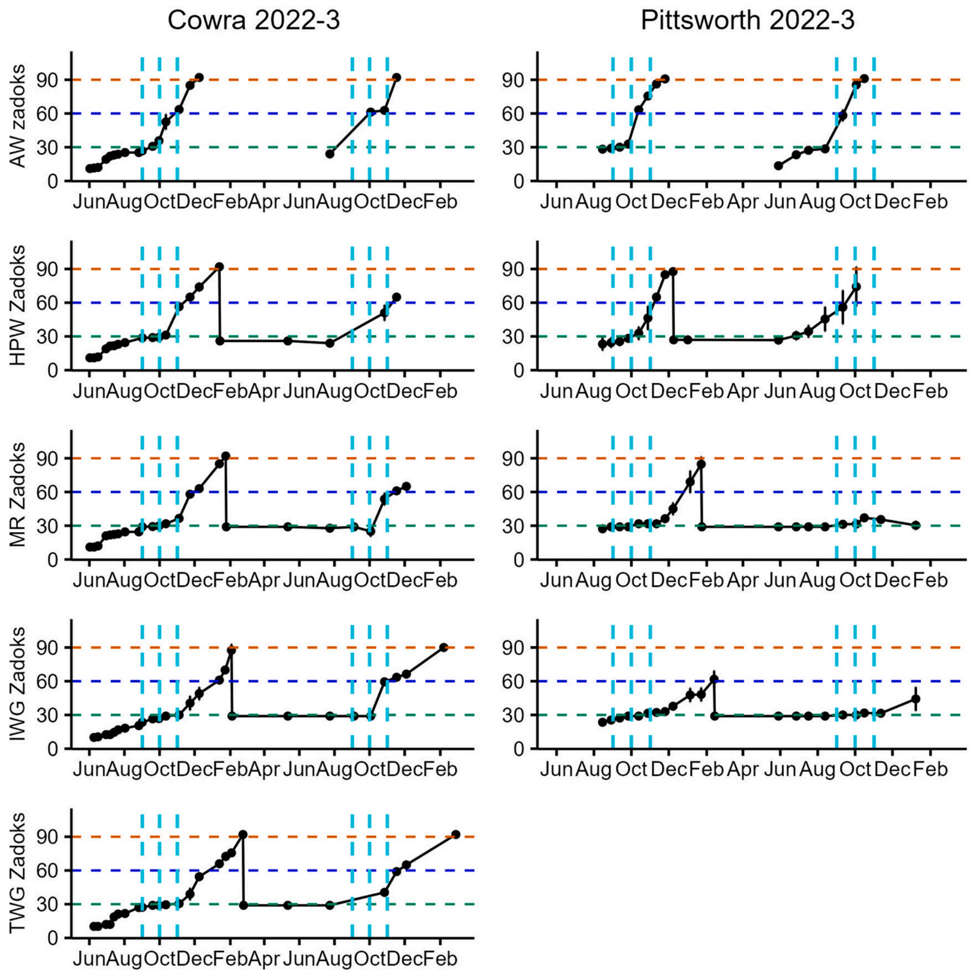

Fig. 2. Each panel represents the Zadoks scores (black dots with bars=SEM) vs. dates of individual species (no-defoliation groups) at Cowra, NSW, AUS and Pittsworth, Qld, AUS for year 1 and year 2 of each experiment. The green horizontal line represents the transition to the reproductive stage, the blue line anthesis, and the orange grain ripe stage. The vertical bars are reference marks for the months of September, October, and November.

and grain production of the AW in year 1 and year 2 (Table 8 and Table 9), similar to the result observed by Hayes et al. (2012). The biomass of MR and IWG were also higher at Pittsworth compared to AW (Table 9). The MR and IWG at Pittsworth however, produced no grain in year 2 (Table 8), with percentage grain yields compared to AW lower than those of the MR and IWG at Cowra (Table 9). Thus, the hypothesis that the cooler climate species (MR and IWG) would have lower grain production (when compared to AW) at Pittsworth than at Cowra was confirmed. Hybrid perennial wheat had higher biomass and grain yields at Pittsworth than at Cowra (Table 8 and Table 9), therefore, the conjecture that HPW would have similar performance at both locations was not confirmed. However, soil type differences between locations, rainfall extent and timing, and disease occurrence, may all have been confounding factors in the production of these results. The possible cause of the MR and IWG failures at Pittsworth may relate to their higher chilling requirements relative to AW (Innes et al., 2025), and their slow maturing rate. In lower latitude environments, such as Pittsworth, this may expose them to heat and moisture stress at a key stage of their reproductive cycle.

Vernalisation and induction requirements are an important determinant of the progression from vegetative to reproductive growth of many cool season perennial grasses such as IWG, MR and TWG (Barriball et al., 2022; Duchene et al., 2021; Ivancic et al., 2021; Kemp et al., 1989). It is important that the reproductive triggers (cool temperature and short day exposure followed by long day exposure) are satisfied before the onset of damaging higher temperatures (Heide, 1994). These are important determinants of grain production at different latitudes. Cereals are more sensitive to heat stress during the reproductive phase of development than during vegetative growth (Shewry, 2009). Exposure to high temperature during the reproductive phase can impair grain yield through several causes, including reduced pollen viability (Ullah et al., 2022), a reduction in spike number (Tiwari et al., 2017), and limitations to grain filling (Farooq et al., 2011; Zenda et al., 2022). In the Pittsworth experiment, the AW and HPW completed their early reproductive development before the onset of higher maximum temperatures (Fig. 1 and Fig. 2). However, Pittsworth in the second season experienced $> 35^{\circ}C$ during the period when IWG and MR were in their early reproductive stages (i.e. October 2023, Fig. 2). The later maturity of IWG and MR (compared to AW and HPW) possibly relates to their secondary induction requirements, MR seemingly requiring a 12–13 h daylength and IWG a > 13 h daylength (in addition to vernalisation) before proceeding to reproductive development (Innes et al., 2025; Locatelli et al., 2022).The result for IWG at Pittsworth in year 2 was no grain development (Table 8). Similarly, the MR in year 2 in Pittsworth appeared to proceed to reproductive development too late to escape the higher temperatures and produced no grain (Table 8). However, MR also had a low survival rate (25 %, Table 11), possibly due to the combination of higher temperatures and water stress (Fig. 1). The 13-h daylength occurs approximately one week earlier at Cowra than Pittsworth, with relatively cooler temperatures at this stage (Fig. 1). This may explain why at Cowra the IWG produced a small quantity of grain but produced none at Pittsworth (Table 8). The hybrid perennial wheat HPW matured earlier

Fig. 3. Top image if from Cowra, NSW, AUS, Sep. 2022, AW and HPW (centre and left) showing symptoms of disease. Lower image is from Pittsworth, Qld, AUS Oct. 2022, with HPW (left) and AW (right) mostly showing healthy growth.

Table 6
Table of P-values for all variables and their interactions at Cowra, NSW, AUS. Persistence is a measure of surviving plants at the end of each year. TKW is one Thousand Kernel Weight. 'x' indicates interaction.

Cowra P-values				
	Biomass	*Grain yield*	*TKW*	*Persistence*
Year	<0.01	<0.01	0.20	<0.01
Defoliation	0.03	0.01	0.31	0.23
Species	<0.01	<0.01	<0.01	<0.01
Year x Defoliation	0.10	0.21	0.99	0.66
Year x Species	<0.01	<0.01	0.58	<0.01
Defoliation x Species	0.03	0.01	0.11	0.20

Table 7
Table of P-values for all variables and their interactions at Pittsworth, Qld, AUS. Persistence is a measure of surviving plants at the end of each year. TKW is one Thousand Kernel Weight. 'x' indicates interaction.

Pittsworth P-values				
	Biomass	*Grain yield*	*TKW*	*Persistence*
Year	<0.01	<0.01	0.01	<0.01
Defoliation	0.60	0.92	0.65	0.91
Species	<0.01	<0.01	<0.01	<0.01
Year x Defoliation	0.38	0.89	0.29	0.77
Year x Species	<0.01	<0.01	<0.01	<0.01
Defoliation x Species	0.69	0.99	0.87	0.11

than IWG and MR (Fig. 2) and had the highest grain yield of all species in the second season at Pittsworth (Table 8). This result accords to some extent with the results of Hayes et al. (2018), who found that species derived from *Th. ponticum* (such as HPW) performed better than *Th. intermedium* derivatives when grown at lower latitudes. However, in other experiments, e.g. Hayes et al. (2017), hybrid wheats have shown a sharp decline in density in the second season compared to other perennials such as IWG. This was attributed to a summer that was hotter and dryer than average (Hayes et al., 2017).

The lack of significant results from the defoliation treatments (Table 6) may be partly the result of the experimental design. The aim was to simulate the effects of grazing or harvesting a paddock of mixed species. Because of this, the defoliations were timed to the growth stage of the fastest developing species, i.e., annual wheat. For the slower developing species, this meant little, or no biomass was harvested at the first defoliation in many cases, as the plants had barely reached the defoliation height of 10 cm. So, while the method used may be suitable for simulating the results of grazing a mixed pasture, it did not give a good indication of how the individual species respond to defoliation.

At Cowra the undefoliated treatment produced the highest biomass

Table 8
The main effects of species on mean biomass, grain yield, and thousand kernel weight (TKW) recorded in year 1 (Y1) and year 2 (Y2), at Cowra, NSW, AUS and Pittsworth, Qld, AUS. For each species, biomass is the mean of the total sum of plant material from defoliations and harvest in year 1, and the sum of harvested biomass and grain in year 2. Biomass and grain yields are expressed as the weight in grams of all plants in the centre row of each plot (g/m). There were no significant interaction effects between defoliation treatment and species. Column values that share a letter are not significantly different (p > 0.05). NS=Not Significant.

	Cowra						*Pittsworth*					
Species	***Biomass***		***Grain***		***TKW***		***Biomass***		***Grain***		***TKW***	
	g/m		***g/m***		***g***		***g/m***		***g/m***		***g***	
	Y1	**Y2**	**Y1**	**Y2**	**Y1**	**Y2**	**Y1**	**Y2**	**Y1**	**Y2**	**Y1**	**Y2**
HPW	52.6c	0	5.6c	0	21.6b		546.7a	321.7a	169.0a	14.9a	31.3b	26.4
MR	512.0a	12.6b	60.1a	0.1c	11.0c	7.3b	429.8b	85.5b	30.3c	0	9.0c	-
AW	82.8bc	26.2b	27.5b	9.0a	29.0a	33.3a	202.9c	43.9b	91.6b	0.7b	37.1a	25.5
IWG	60.1c	24.3b	2.9c	0.6bc	8.3c	6.9bc	160.0c	103.1b	0.2d	0	7.7d	-
TWG*	158.4b	124.9a	12.6c	3.3b	13.0c	4.9c						
P Value	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*0.78*
LSD (P = 0.05)	*79.0*	*46.7*	*14.9*	*3.0*	*7.2*	*2.0*	*107.5*	*90.8*	*24.1*	*3.9*	*1.1*	*NS*

* TWG not sown at Pittsworth

Table 9
Percentage yields (year 1, year 2, and year 1 +year 2) of each species compared to wheat yield at Cowra, NSW, AUS and Pittsworth, Qld, AUS. Biomass is the total sum of plant material from defoliations and harvest in year 1, and the sum of harvested biomass and grain in year 2.

	Cowra % of AW yield						*Pittsworth % of AW yield*					
	Biomass			***Grain***			***Biomass***			***Grain***		
	Y1	***Y2***	***Y1+Y2***	***Y1***	***Y2***	***Y1+Y2***	***Y1***	***Y2***	***Y1+Y2***	***Y1***	***Y2***	***Y1+Y2***
	%	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*
HPW	64	0	48	20	0	15	269	733	353	185	213	199
MR	618	48	481	219	1	165	212	195	209	33	0	33
IWG	73	93	77	11	1	10	79	235	108	0	0	0
TWG*	191	477	260	46	37	44						

* TWG not sown at Pittsworth

Table 10
The main effect of defoliation on biomass, grain yields, and thousand kernel weight (TKW) by defoliation regime, in year 1 at Cowra, NSW, AUS and Pittsworth, Qld, AUS. Biomass is the sum of plant material from all defoliations and harvest. Column values that share a letter are not significantly different (p > 0.05). NS=Not Significant.

	Cowra			*Pittsworth*		
Defoliation	***Biomass***	***Grain***	***TKW***	***Biomass***	***Grain***	***TKW***
	g/m	***g/m***	***g***	***g/m***	***g/m***	***g***
None	234.3a	35.3a	16.3	365.9	68.8	22.1
Early	151.0b	21.1b	20.5	344.0	71.4	22.5
Late	129.4b	12.4b	15.0	340.3	75.8	21.5
Early+Late	178.1ab	18.2b	14.5	289.3	73.8	24.5
P Value	*0.03*	*< 0.01*	*0.24*	*0.54*	*0.91*	*0.96*
LSD (P = 0.05)	*70.7*	*13.3*	*NS*	*NS*	*NS*	NS

Table 11
The main effect of species on the mean number of surviving plants (mountain rye (MR), hybrid perennial wheat (HPW), intermediate wheatgrass (IWG), tall wheatgrass (TWG)) from the ten originally planted in the middle row of each plot at Cowra, NSW, AUS and Pittsworth, Qld, AUS. Plant counts were completed at the end of the first year (year 1) and second year (year 2) of growth. Column values that share a letter are not significantly different (p > 0.05). NS=Not Significant.

	Cowra plant persistence		*Pittsworth plant persistence*	
Species	***Year 1***	***Year 2***	***Year 1***	***Year 2***
MR	9.9 a	1.5	9.6	0.9 b
HPW	6.5 bc	0	9.4	5.8 a
IWG	5.7c	1.7	9.7	5.9 a
TWG	6.1 bc	2.4	na*	na*
P value	*<0.01*	*0.10*	*0.80*	*<0.01*
LSD(P = 0.05)	*1.1*	*NS*	*NS*	*1.4*

* not sown at this site

and grain yields, averaged across species, in the first season (Table 10). However, Hunter et al. (2020a), in a defoliation experiment using IWG, found that a single autumn defoliation produced the highest biomass, and that defoliations in general increased tiller numbers and grain production (however, neither row spacing nor defoliation affected a general decline in grain yields over a four year period). Puka-Beals et al. (2022) reported higher cumulative forage yields with IWG when there were two to three defoliations rather than just one.

Defoliation biomass results may also have been affected by disease factors at Cowra (see Fig. 3), with diseased plants producing reduced biomass. Disease management has been flagged as an issue in perennial cereals, with pathogens possibly surviving for several years in the soil, roots and plant parts of perennial cereals (Soto-Gómez and Pérez-Rodríguez, 2022). The timing of the phenology, and how it is synchronised with the temperature and daylength (Fig. 1), also has a bearing on the timing of biomass production (Fig. 2). Pittsworth has warmer winter temperatures (Table 2) and relatively high nutrient soil compared to Cowra (Table 3). With favourable rainfall in year 1 (Fig. 1), and the with defoliations carried out early in the season (before stem elongation) there was more early growth at Pittsworth than at Cowra (Fig. 3). The cumulative biomass from the defoliations and harvest were correspondingly higher. This early season growth at Pittsworth possibly obscured any effects from the different defoliation regimes at this location.

5. Conclusion

Neither IWG nor MR were well suited for grain production in the lower latitude Pittsworth environment. Their later maturity renders them vulnerable to heat and moisture stress during key stages of their reproductive development. Cowra has a higher latitude and the photoperiod timing, in respect to higher summer temperatures, was more favourable for IWG and MR grain production. The improved understanding of the reproductive triggers of both MR and IWG will assist growth modelling to help clarify the management strategies that will optimise production from these perennial cereals. Future development of perennial cereals with shorter maturity times, closer to those of AW, while maintaining persistence in warmer and dryer climates, could further extend the potential geographical range for perennial grain production in Australia.

CRediT authorship contribution statement

Innes Peter Joseph: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M.T. Newell:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **K.G. Pembleton:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **R.C. Hayes:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **A.M. Radanielson:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data link is in the data availability section of the manuscript

References

Australian Bureau of Meteorology. (2025, 2025/03/03/). Climate statistics for Australian locations. Retrieved from ⟨http://www.bom.gov.au/climate/averages/tables/cw_041023_All.shtml⟩.

Bajgain, P., Crain, J.L., Cattani, D.J., Larson, S.R., Altendorf, K.R., Anderson, J.A., DeHaan, L.R., 2022. Breeding Intermediate Wheatgrass for Grain Production. Plant Breeding Reviews. John Wiley & Sons, Ltd, Chichester, England, UK, pp. 119–217.

Barriball, S. (2020). *Growth, development, and forage quality of Intermediate wheatgrass when grown for Kernza® perennial grain production.* Retrieved from ⟨https://dr.lib.iastate.edu/entities/publication/3a301ffa-e78b-418d-aa3a-24cb301c0e74⟩.

Barriball, S., Han, A., Schlautman, B., 2022. Effect of growing degree days, day of the year, and cropping systems on reproductive development of Kernza in Kansas. Agrosystems Geosci. Environ. 5 (3), e20286. https://doi.org/10.1002/agg2.20286.

Bell, L.W., Moore, A.D., 2012. Integrated crop–livestock systems in Australian agriculture: Trends, drivers and implications. Agric. Syst. 111, 1–12. https://doi.org/10.1016/j.agsy.2012.04.003.

Bell, L.W., Wade, L.J., Ewing, M.A., 2010. Perennial wheat: A review of environmental and agronomic prospects for development in Australia. Crop Pasture Sci. 61 (9), 679–690. https://doi.org/10.1071/CP10064.

Chapman, E.A., Thomsen, H.C., Tulloch, S., Correia, P.M.P., Luo, G., Najafi, J., Palmgren, M., 2022. Perennials as Future Grain Crops: Opportunities and Challenges. Front. Plant Sci. 13. https://doi.org/10.3389/fpls.2022.898769.

Chouard, P., 1960. Vernalization and its Relations to Dormancy. Annu. Rev. Plant Biol. 11 (1960), 191–238. https://doi.org/10.1146/annurev.pp.11.060160.001203.

Clements, B., Ayres, L., Langford, C., McGarva, L., Simpson, P., Hennessy, G., … Leech, F. (2003). The grazier's guide to pastures:Sowing and managing profitable pastures in the central and southern Tablelands, Monaro and Upper South West Slopes of New South Wales. Retrieved from ⟨https://www.dpi.nsw.gov.au/agriculture/pastures-and-rangelands/establishment-mgmt/grazing-management2/graziers-guide-pastures⟩.

Cox, T.S., Glover, J.D., Van Tassel, D.L., Cox, C.M., DeHaan, L.R., 2006. Prospects for Developing Perennial Grain Crops. Bioscience 56 (8), 649–659 doi:10.1641/0006-3568(2006)56[649:Pfdpgc]2.0.Co;2.

Crews, T.E., Blesh, J., Culman, S.W., Hayes, R.C., Jensen, E.S., Mack, M.C., Schipanski, M.E., 2016. Going where no grains have gone before: From early to mid-succession. Agric. Ecosyst. Environ. 223, 223–238. https://doi.org/10.1016/j.agee.2016.03.012.

Crews, T.E., Carton, W., Olsson, L., 2018. Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. Glob. Sustain. 1. https://doi.org/10.1017/sus.2018.11.

Duchene, O., Celette, F., Barreiro, A., Mårtensson, L.M.D., Freschet, G.T., David, C., 2020. Introducing perennial grain in grain crops rotation: The role of rooting pattern in soil quality management. Agronomy 10 (9). https://doi.org/10.3390/agronomy10091254.

Duchene, O., Dumont, B., Cattani, D.J., Fagnant, L., Schlautman, B., DeHaan, L.R., Celette, F., 2021. Process-based analysis of Thinopyrum intermedium phenological development highlights the importance of dual induction for reproductive growth and agronomic performance. Agric. For. Meteorol. 301, 108341. https://doi.org/10.1016/j.agrformet.2021.108341.

Farooq, M., Bramley, H., Palta, J.A., Siddique, K.H.M., 2011. Heat Stress in Wheat during Reproductive and Grain-Filling Phases. Crit. Rev. Plant Sci. 30 (6), 491–507. https://doi.org/10.1080/07352689.2011.615687.

Favre, J.R., Castiblanco, T.M., Combs, D.K., Wattiaux, M.A., Picasso, V.D., 2019. Forage nutritive value and predicted fiber digestibility of Kernza intermediate wheatgrass in monoculture and in mixture with red clover during the first production year. Anim. Feed Sci. Technol. 258, 114298. https://doi.org/10.1016/j.anifeedsci.2019.114298.

Freer, M., Donnelly, J.R., Axelsen, A., Myers, L.F., Davidson, J.L., Dymock, J., 1997. Comparison of secale with other perennial grasses under grazing at a cool site in the high rainfall zone of New South Wales. Aust. J. Exp. Agric. 37 (1), 19–25. https://doi.org/10.1071/ea96062.

Harmoney, K.R., 2005. Growth Responses of Perennial Cool-Season Grasses Grazed Intermittently. Forage Grazing 3 (1), 1–8. https://doi.org/10.1094/fg-2005-0105-01-rs.

Hayes, R.C., Newell, M.T., Crews, T.E., Peoples, M.B., 2017. Perennial cereal crops: An initial evaluation of wheat derivatives grown in mixtures with a regenerating annual legume. Renew. Agric. Food Syst. 32 (3), 276–290. https://doi.org/10.1017/S1742170516000260.

Hayes, R.C., Newell, M.T., DeHaan, L.R., Murphy, K.M., Crane, S., Norton, M.R., 2012. Perennial cereal crops: An initial evaluation of wheat derivatives. Field Crops Res. 133, 68–69. https://doi.org/10.1016/J.FCR.2012.03.014.

Hayes, R.C., Newell, M.T., Larkin, P.J., Bell, L.W., & Llewellyn, R.S. (2017a). Prospects for perennial grains in Australian farming systems – An overview. "*Doing More with Less*", *Proceedings of the 18th Australian Society of Agronomy Conference 2017, Ballarat, Victoria, Australia, 24-28 September 2017 (pp. 1-4) Australian Society of Agronomy Inc.* Retrieved from ⟨http://www.agronomyaustraliaproceedings.org/⟩.

Hayes, R.C., Wang, S., Newell, M.T., Turner, K., Larsen, J., Gazza, L., Li, G.D., 2018. The performance of early-generation perennial winter cereals at 21 sites across four continents. Sustain. (Switz.) 10 (4), 1–28. https://doi.org/10.3390/su10041124.

Heide, O.M., 1994. Control of flowering and reproduction in temperate grasses. N. Phytol. 128 (2), 347–362. https://doi.org/10.1111/j.1469-8137.1994.tb04019.x.

Hunter, M.C., Sheaffer, C.S., Culman, S., Jungers, J.M., 2020a. Effects of defoliation and row spacing on intermediate wheatgrass I: Grain production. Agron. J. 112 (3), 1748–1763. https://doi.org/10.1002/agj2.20128.

Hunter, M.C., Sheaffer, C.S., Culman, S., Lazarus, W., Jungers, J.M., 2020b. Effects of defoliation and row spacing on intermediate wheatgrass II: Forage yield and economics. Agron. J. 112 (3), 1862–1880. https://doi.org/10.1002/agj2.20124.

Innes, P.J., Newell, M.T., Pembleton, K.G., Hayes, R.C., Radanielson, A.M., 2025. A study of the vernalisation requirements of mountain rye (Secale strictum syn. S. montanum) may help explain low grain yields of perennial cereals compared to wheat. AoB PLANTS 17 (2). https://doi.org/10.1093/aobpla/plaf015.

Innes, P.J., Tan, D.K., Van Ogtrop, F., Amthor, J.S., 2015. Effects of high-temperature episodes on wheat yields in New South Wales, Australia. Agric. For. Meteorol. 208, 95–107. https://doi.org/10.1016/j.agrformet.2015.03.018.

Isbell, R., 2016. The Australian soil classification. CSIRO publishing.

Ivancic, K., Locatelli, A., Tracy, W.F., Picsasso, V., 2021. Kernza intermediate wheatgrass (Thinopyrum intermedium) response to a range of vernalization conditions. Can. J. Plant Sci. 101 (5), 770–773. https://doi.org/10.1139/cjps-2020-0251.

Kemp, D.R., Eagles, C.F., Humphreys, M.O., 1989. Leaf Growth and Apex Development of Perennial Ryegrass During Winter and Spring. Ann. Bot. 63 (3), 349–355. https://doi.org/10.1093/oxfordjournals.aob.a087751.

Larkin, P.J., Newell, M.T., Hayes, R.C., Aktar, J., Norton, M.R., Moroni, S.J., Wade, L.J., 2014. Progress in developing perennial wheats for grain and grazing. Crop Pasture Sci. 65 (11), 1147–1164. https://doi.org/10.1071/CP13330.

Locatelli, A., Gutierrez, L., Picasso Risso, V.D., 2022. Vernalization requirements of Kernza intermediate wheatgrass. Crop Sci. 62 (1), 524–535. https://doi.org/10.1002/csc2.20667.

McGrath, S.R., Behrendt, R., Friend, M.A., Moore, A.D., 2021. Utilising dual-purpose crops effectively to increase profit and manage risk in meat production systems. Anim. Prod. Sci. 61 (11), 1049–1061. https://doi.org/10.1071/an20495.

Newell, M.T., 2021. Proceedings of the Perennial Artisan Grain Workshop. Cowra, 15-17 June. In: Newell, M.T. (Ed.), Agrifutures Australia. Agrifutures Australia, Wagga Wagga, NSW.

Newell, M.T., Baker, S., Sinclair, K., Hayes, R.C., & Salkeld, E. (2021). *Hedonic exploration of sensory attributes from sourdough loaves made from perennial wheat* Paper presented

at the Proceedings of the Perennial Artisan Grains Workshop 15–17 June 2021, Australia.
Newell, M.T., Hayes, R.C., 2017. An initial investigation of forage production and feed quality of perennial wheat derivatives. Crop Pasture Sci. 68 (12), 1141–1148. https://doi.org/10.1071/CP16405.
Newell, M.T., & Hayes, R.C. (2023). *Potential of Mountain Rye (Secale strictum) As a Domesticated Perennial Grain for Australia: An Overview*. Paper presented at the ASA, CSSA, SSSA International Annual Meeting.
Newell, M.T., Holman, B.W.B., Refshauge, G., Shanley, A.R., Hopkins, D.L., Hayes, R.C., 2020. The effect of a perennial wheat and lucerne biculture diet on feed intake, growth rate and carcass characteristics of Australian lambs, 106235-106235 Small Rumin. Res. 192. https://doi.org/10.1016/j.smallrumres.2020.106235.
Oram, R.N., 1996. Secale montanum—a wider role in Australasia? N. Z. J. Agric. Res. 39 (4), 629–633. https://doi.org/10.1080/00288233.1996.9513223.
Pleming, D., Newell, M., Hayes, R.C., Tang, K.H., Penrose, B., Wilson, M., Blanchard, C., 2023. An investigation of grain characteristics, dough quality and baking performance of perennial wheats from contrasting parentage. J. Cereal Sci. 114, 103798. https://doi.org/10.1016/j.jcs.2023.103798.
Pugliese, J.Y., Culman, S.W., Sprunger, C.D., 2019. Harvesting forage of the perennial grain crop kernza (Thinopyrum intermedium) increases root biomass and soil nitrogen cycling. Plant Soil 437, 241–254. https://doi.org/10.1007/s11104-019-03974-6.
Puka-Beals, J., Sheaffer, C.C., Jungers, J.M., 2022. Forage yield and profitability of grain-type intermediate wheatgrass under different harvest schedules. Agrosystems Geosci. Environ. 5 (3), e20274. https://doi.org/10.1002/agg2.20274.
Rayment, G., & Lyons, D. (2010). *Soil Chemical Methods - Australasia*.
R-Core-Team. (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from ⟨https://www.R-project.org/⟩.
Shewry, P.R., 2009. Wheat. J. Exp. Bot. 60 (6), 1537–1553. https://doi.org/10.1093/jxb/erp058.
Soto-Gómez, D., Pérez-Rodríguez, P., 2022. Sustainable agriculture through perennial grains: Wheat, rice, maize, and other species. A review, 107747-107747 Agric. Ecosyst. Environ. 325. https://doi.org/10.1016/J.AGEE.2021.107747.
Tiwari, A., Prasad, S., Jaiswal, B., Gyanendra, K., Singh, S., Singh, K., 2017. Effect of Heat Stress on Yield Attributing Traits in Wheat (Triticum aestivum L.). Int. J. Curr. Microbiol. Appl. Sci. 6, 2738–2744. https://doi.org/10.20546/ijcmas.2017.612.317.
Ullah, A., Nadeem, F., Nawaz, A., Siddique, K.H.M., Farooq, M., 2022. Heat stress effects on the reproductive physiology and yield of wheat. J. Agron. Crop Sci. 208 (1), 1–17. https://doi.org/10.1111/jac.12572.
Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stages of cereals. Weed Res. 14 (6), 415–421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x.
Zenda, T., Wang, N., Dong, A., Zhou, Y., Duan, H., 2022. Reproductive-Stage Heat Stress in Cereals: Impact, Plant Responses and Strategies for Tolerance Improvement. Int. J. Mol. Sci. 23 (13), 6929. https://doi.org/10.3390/ijms23136929.