**Effect of stubble height management on perennial ryegrass, tall fescue, and chicory crown temperature**

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Above optimal ambient temperatures (≥30˚C) challenge summer pasture production in south-eastern Australia. A field experiment showed defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) contributed to elevating the crown temperature of three pasture species, which may have negative implications for plant growth and survival during hot summers. Chicory (*Cichorium intybus* L.) experienced less extreme crown temperatures than perennial ryegrass (*Lolium perenne* L.), which may partly contribute to chicory’s superior growth in hot summer environments.

# Abstract

Defoliating pasture to shorter stubble heights (height of stubble above the soil surface) may increase temperature at the plant crown (plant-soil interface). A rain-fed field experiment in north-west Tasmania, Australia, quantified the effect of stubble height management on the upper distribution of crown temperatures (90th and 75th percentiles) experienced by three pasture species. Species examined included perennial ryegrass (*Lolium perenne* L.), tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort.; syn. *L. arundinaceum* (Schreb.) Darbysh.], and chicory (*Cichorium intybus* L.). Three stubble height treatment levels were evaluated, *viz.* 35 mm, 55 mm, and 115 mm. Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) increased the crown temperature of all species in the subsequent regrowth cycle (period between successive defoliation events). In the second summer, defoliating to shorter stubble heights increased the 90th percentile of crown temperature by an average of 4.2˚C for perennial ryegrass, 3.6˚C for tall fescue, and 1.8˚C for chicory. Chicory and second year tall fescue swards experienced less extreme crown temperatures than perennial ryegrass. This may partly explain the increasing interest in the use of these species to out-yield perennial ryegrass in hotter summer environments than north-west Tasmania.

# Additional keywords

Defoliation severity, grazing intensity, grazing management, leaf area index, mechanical defoliation, residual height

# Introduction

In many south-eastern (SE) Australian dairying regions, summer pasture production can be constrained by above optimal (supraoptimal) ambient temperatures (Ta) (≥30˚C). This is due to the minimal supraoptimal temperature tolerance of the main sown pasture species, perennial ryegrass (*Lolium perenne* L.) ([Mitchell 1956](#_ENREF_37); [Jacobs and Woodward 2010](#_ENREF_24)). Even with adequate irrigation, supraoptimal temperatures challenge perennial ryegrass growth and survival ([Arcioni *et al.* 1985](#_ENREF_3); [Neal *et al.* 2009](#_ENREF_40)). Potential mitigation strategies pertain to both management, and incorporation of species more tolerant of supraoptimal temperature stress into the feed-base such as continental (summer-active) tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort.; syn. *L. arundinaceum* (Schreb.) Darbysh.] and chicory (*Cichorium intybus* L.) ([Jiang and Huang 2001](#_ENREF_25); [Langworthy *et al.* 2018](#_ENREF_30)). An added advantage of tall fescue and chicory is that they possess key attributes underpinning perennial ryegrass’s popularity ([Wilkins 1991](#_ENREF_56)); i.e. they are perennial ([Rumball 1986](#_ENREF_47); [Raeside *et al.* 2012b](#_ENREF_45)), grazeable ([Raeside *et al.* 2012a](#_ENREF_44); [Lee *et al.* 2015](#_ENREF_33)), and of high nutritive value ([Chapman *et al.* 2008](#_ENREF_10); [Muir *et al.* 2015](#_ENREF_38)).

Defoliation management is one aspect of feed-base management requiring consideration, as defoliation can result in the elevation of plant crown (plant-soil interface) temperatures ([Harrison *et al.* 2015](#_ENREF_22)). This is partly due to the reduced post-defoliation canopy leaf area index (LAI) permitting more solar radiation (SR) and sensible heat interception at the crown (i.e. direct radiation heat exchange). This mechanism has been confirmed in winter wheat ([Harrison *et al.* 2015](#_ENREF_22)) and used to explain the amplification of soil temperature close to the surface (pedoderm): (i) following and during defoliation events ([Bremer *et al.* 1998](#_ENREF_7); [Tanaka and Hashimoto 2006](#_ENREF_51)); and (ii) under fallow vs. pasture ([Black and Aase 1988](#_ENREF_5); [Grant *et al.* 1995](#_ENREF_19)). In water-limited environments, greater SR interception at the canopy base may indirectly elevate crown temperature by reducing soil water content near the pedoderm ([Black and Aase 1988](#_ENREF_5); [Matthew 1992](#_ENREF_35); [Liu *et al.* 2011](#_ENREF_34)). Reductions in soil water content can make soil surrounding the crown more susceptible to temperature increases ([Ghuman and Lal 1985](#_ENREF_18); [Abu-Hamdeh 2003](#_ENREF_1); [Arkhangelskaya *et al.* 2015](#_ENREF_4)), while reducing the potential for evaporative cooling ([Bremer *et al.* 2001](#_ENREF_6)).

Defoliation induced elevations in crown temperature, during periods of supraoptimal temperature stress, may negatively affect growth and survival of pasture species. This is due to the indeterminate meristematic tissue (apical meristem) responsible for phytomer production being situated at the crown during vegetative growth ([Rumball 1986](#_ENREF_47); [Korte *et al.* 1987](#_ENREF_28); [Yang *et al.* 1998](#_ENREF_57)). Phytomers are the basic repeating unit of vegetative growth, consisting of a leaf, internode, axillary bud, and one or more root primordia ([Briske 1991](#_ENREF_8); [Gautier *et al.* 2001](#_ENREF_17); [Skinner and Moore 2007](#_ENREF_49)). Supraoptimal crown temperatures may reduce growth rates and challenge plant survival by: (i) impeding phytomer production via damage to the apical meristem ([Mitchell and Lucanus 1962](#_ENREF_36)); (ii) damaging axillary bud development ([Faust and Heins 1996](#_ENREF_14); [Schoellhorn *et al.* 2001](#_ENREF_48)), thereby limiting future tillering/shoot development ([Mitchell 1956](#_ENREF_37); [Knievel and Smith 1973](#_ENREF_26)); and (iii) damaging existing axillary buds and root primordia ([Dernoeden 2012](#_ENREF_12)).

Reducing the intensity of defoliation events (i.e. leaving a higher post-defoliation LAI) during hot summers may potentially limit plants’ exposure to supraoptimal crown temperatures. In practice, defoliation intensity is more easily estimated by targeting a specific post-defoliation stubble height (height of stubble above the soil surface) than LAI ([Rawnsley *et al.* 2014](#_ENREF_46)). This paper reports on a rain-fed field experiment established to test the hypothesis that defoliating to shorter stubble heights would elevate perennial ryegrass, tall fescue, and chicory crown temperatures. The experiment also tested the hypothesis that when defoliated to the same stubble height, interspecies crown temperature differences would exist. Confirmation of this hypothesis may assist in explaining the differential tolerance of these species to supraoptimal temperature stress.

# Materials and methods

All data was collected from rain-fed (nil-irrigated) plots used in a larger study quantifying stubble height and irrigation management effects on the growth, botanical composition and persistence of perennial ryegrass, tall fescue, and chicory swards ([Langworthy *et al.* submitted](#_ENREF_29)).

The experiment was conducted between September 2015 and April 2017 at the Tasmanian Institute of Agriculture Dairy Research Facility (41˚08’S, 145˚77’E; 155.0 m a.m.s.l), Elliott, north-west (NW) Tasmania, Australia. The location is characterised by a cool-temperate climate and winter-dominant rainfall pattern (mean annual rainfall, 1179 mm). The experimental site had minimal undulations, and a Red Mesotrophic Haplic Ferrosol soil ([Isbell 1996](#_ENREF_23)). Additional site and soil details are provided in [Langworthy *et al.* (submitted)](#_ENREF_29).

When considered in isolation, plots included in this experiment were arranged in a randomised complete block (RCB) design that included four replicates arranged as blocks. A total of 36 plots were included (four blocks by three pasture species by three stubble height treatments). Each plot measured 2 m by 3 m and was surrounded by a 0.5 m buffer of the selected pasture species.

On 17September 2015, pasture species were sown into a fully prepared seedbed with an Oyjard small-plot drill (150 mm row spacing, 10 mm sowing depth). Tetraploid perennial ryegrass cv. Bealey® (NEA2, non-toxic endophyte), tall fescue cv. Quantum II® (MaxP®, non-toxic endophyte), and chicory cv. Puna® were sown at 25, 25, and 10 kg of uncoated seed/ha, respectively. Over 116 days, swards were established under spray irrigation and 300 mm of irrigation water was applied. Seventy-seven days after sowing (3 December 2015), swards were defoliated with a rotary lawnmower to a ~70 mm stubble height (Victa Mustang; Briggs and Stratton Corporation, Milwaukee, USA); cut herbage was removed, and no fertiliser applied. Detailed seedbed preparation and establishment descriptions are provided in [Langworthy *et al.* (submitted)](#_ENREF_29).

On 7 January 2016 irrigation ceased (i.e. plots were rain-fed from this point onwards), and on 11-12 January 2016 swards were defoliated to their respective stubble height treatments (D1). Swards were mechanically defoliated using a rotary lawnmower (SXG326; Iseki and Co., Ltd., Tokyo, Japan), with all cut herbage removed from plots. Cutting heights were set to leave a stubble height of either 35 mm, 55 mm, or 115 mm. Swards were defoliated to these stubble height treatments on twelve more occasions, denoted D2 (9-10 February 2016), D3 (15-16 March 2016), D4 (27-28 April 2016), D5 (21-22 June 2016), D6 (23-24 August 2016), D7 (12-14 October 2016), D8 (9-10 November 2016), D9 (9-10 December 2016), D10 (4-5 January 2017), D11 (1-2 February 2017), D12 (8-9 March 2017), and D13 (12-13 April 2017) (Fig. 1). Scheduled defoliation events were based on the physiological status of irrigated perennial ryegrass (part of the larger study). Defoliation events occurred when the mean leaf regrowth stage of irrigated perennial ryegrass plants equalled 2.5 leaves/tiller. Defoliation events were occasionally scheduled at an earlier leaf regrowth stage (2.0 leaves/tiller) to prevent canopy closure or minimise reproductive development.

Immediately following each defoliation event, 50 kg nitrogen (N)/ha (as urea, 46% N) was applied to prevent growth from becoming N limited. On 27 October and 25 November 2016, 80 kg muriate of potash/ha (50% potassium) and 511.4 kg single superphosphate/ha (8.8% phosphorus, 11% sulphur, and 19% calcium) was applied. Chlorpyrifos (0.9 L/ha of Apparent Dingo 500 at 0.45 kg active ingredient/ha; Apparent Pty Ltd, Hawthorn East, Vic., Australia) was sprayed once (15 February 2016) to control *Persectania ewingii* (Westwood) and *Teleogryllus commodus* (Walker).

[Insert Fig. 1 near here]

During the experiment, ambient temperature and SR were logged at 5 min intervals by an on-site automatic weather station (Vantage Pro2; Davis® Instruments Corporation, California, USA). Crown temperature was monitored in three blocks (27 plots). In each plot, crown temperature was monitored via 2-3 self-contained, waterproof thermometers (DS1921G; Thermochron iButton Dallas Semiconductors, San Jose, CA, USA), with an accuracy of ±1˚C between -30˚C to 70˚C. Each thermometer was deployed ≥0.5 m inside the plot perimeter, and vertically inserted into the plant crown so that half of the thermometer (~8.7 mm) sat below the soil surface. Crown temperature was recorded during multiple regrowth cycles, within two growing seasons. Growing season one consisted of three regrowth cycles, including RC1 (summer, D1-D2), RC2 (summer, D2-D3), and RC3 (autumn, D3-D4). Six regrowth cycles comprised growing season two, including RC1 (spring, D7-D8), RC2 (spring, D8-D9), RC3 (summer, D9-D10), RC4 (summer, D10-D11), RC5 (summer, D11-D12), and RC6 (autumn, D12-D13) (Fig. 1). On average, thermometers were deployed to start logging 3 days post-defoliation (range, 2-5 days), and removed 2 days before the subsequent defoliation event (range, 1-3 days). Crown temperature was logged at 30 min intervals.

Relative canopy LAI was measured using a non-destructive canopy analysis system (SunSCAN model SS1-R3-BF3; Delta-T Devices Ltd, Cambridge, UK). Absorption and ellipsoidal leaf angle distribution constants were set at 0.85 and 1.0, respectively. In each monitored regrowth cycle, canopy LAI was measured on four or more occasions. In growing season one, measurements were taken during RC1 (15 January, 20 January, 1 February, and 8 February 2016), RC2 (13 February, 21 February, 27 February, 6 March, and 12 March 2016), and RC3 (19 March, 28 March, 4 April, 11 April, 20 April, and 25 April 2016) (Fig. 1). In growing season two, measurements were only taken during the final four regrowth cycles. These included RC3 (12 December, 20 December, 24 December 2016, and 2 January 2017), RC4 (6 January, 12 January, 19 January, and 29 January 2017), RC5 (3 February, 11 February, 18 February, 27 February, and 5 March 2017), and RC6 (10 March, 18 March, 28 March, 5 April, and 10 April 2017) (Fig. 1). At each measurement, overall canopy LAI of each plot was estimated by taking measurements at 0.6, 1.2, 1.8, and 2.4 m increments along the 3 m length of the plot. At each point, the SunSCAN probe was positioned 0.5 m into the plot and flush with the soil surface.

## Statistical analyses

Crown temperature data was analysed separately for each growing season using quantile regression via the QUANTREG procedure in SAS 9.3 (SAS for Windows Release 9.3; SAS Institute, Cary, NC, USA) ([Koenker 2005](#_ENREF_27)).

Prior to quantile regression, an autoregressive time series model of order two was fitted to the mean variable. Also included was: (i) a linear predictor, being Day of regrowth cycle, which removed linear changes; (ii) a quadratic trend Day-2, which removed curvature; and (iii) cosine and sine terms based on the Day variable, which removed diurnal variation. The cosine and sine terms were defined as:

Day\_2c = cos(2 x 3.14159 x Day),

Day\_2s = sin(2 x 3.14159 x Day),

Day\_4c = cos(4 x 3.14159 x Day),

Day\_4s = sin(4 x 3.14159 x Day).

The autoregressive model was developed with PROC AUTOREG in SAS 9.3. Residuals obtained from the model for the time period, 0800-1700 h (Australian eastern standard time; universal time +1000), were used in the quantile regression to assess treatment effects. As this study was concerned with supraoptimal crown temperatures, analyses were restricted to the 75th and 90th percentiles (i.e. upper end of the crown temperature distribution). Quantile regression was used to model the proportion of time-series adjusted data that fell below the 75th and 90th percentiles. Non-significant terms were removed for the model. Associated *P*-values of pairwise comparisons were multiplicity-adjusted using simulation ([Westfall *et al.* 2011](#_ENREF_54)). Unless otherwise stated, differences discussed were significant at the *P*<0.05 level.

Canopy LAI was analysed separately for each species by growing season by regrowth cycle combination. An RCB analysis of variance (ANOVA) was used within a repeated measures context to compare stubble height treatments for each species. The correlation structure of the repeated measures analysis was modelled using a one-dimensional spatial power function, which depended on the number of days since measurements commenced. Quantile-quantile plots of residuals were generated to assess data distributions, and the presence of heteroscedasticity; no transformations were required. Non-significant terms were removed from the model. Least square means were calculated, with pairwise comparisons undertaken for all significant effects. Associated *P*-values were adjusted using Tukey’s adjustment for multiple comparisons. PROC MIXED and PROC PLM in SAS 9.3 were used for the analysis and post-hoc tests, respectively. Unless otherwise stated, differences discussed were significant at the *P*<0.05 level.

# Results

## Weather conditions

In both growing seasons, mean maximum and minimum daily Ta were highest during summer regrowth cycles (Fig. 2a). Summer regrowth cycles included: (i) growing season one, RC1 and RC2; and (ii) growing season two, RC3-RC5. During the experiment, mean monthly maximum and minimum daily Ta deviated minimally (≤2.7˚C) from the long-term average (1975-2014) (Fig. 2b). Mean monthly total daily SR also deviated minimally from the long-term average (≤2.3 MJ/m2) (Fig. 2c).

[Insert Fig. 2 near here]

## Crown temperature

During summer regrowth cycles, crown temperature was, at most, ≥30˚C for 4% of the time (44 hours) in growing season one (RC1 and RC2), and 9% of the time (170 hours) in growing season two (RC3-RC5) (Fig. 3). Crown temperature values ≥35˚C were only experienced by perennial ryegrass and tall fescue. In growing season two, perennial ryegrass crown temperature was ≥35˚C for 2% of the time, when defoliated to a stubble height of 35 mm (39 hours) or 55 mm (41 hours).

[Insert Fig. 3 near here]

For crown temperature regression quantile analyses, significance levels for main-effects and interactions are shown in Table 1. Only the highest order significant (*P*<0.05) interactions are discussed.

[Insert Table 1 near here]

### Growing season one

At the 75th percentile, crown temperature of each species under the 35 mm and 55 mm stubble height treatments did not differ significantly (stubble height by species interaction). At minimum, these values exceeded crown temperature under the 115 mm stubble height treatment by 1.8˚C for perennial ryegrass, 1.5˚C for tall fescue, and 0.7˚C for chicory (Tables 1 and 2). Observed stubble height effects on the 90th percentile of crown temperature differed across regrowth cycles (stubble height by species by regrowth cycle interaction) (Tables 1 and 3). In each regrowth cycle, tall fescue swards defoliated to stubble heights of 35 mm or 55 mm experienced 1.3-2.4°C higher 90th percentiles of crown temperature than those defoliated to 115 mm. Defoliating to shorter stubble heights usually elevated perennial ryegrass and chicory crown temperatures in both RC2 and RC3, but not RC1. In RC1, 90th percentiles of crown temperature for both species remained unaffected by stubble height treatment.

The 75th percentile of crown temperature significantly differed between species in both RC1 and RC2, but not RC3 (species by regrowth cycle interaction) (Tables 1 and 2). In both RC1 and RC2, perennial ryegrass and tall fescue crown temperatures (75th percentile) did not significantly differ, but exceeded chicory crown temperature by an average of 2.2˚C. In each stubble height treatment, perennial ryegrass and tall fescue crown temperatures (75th percentile) did not significantly differ, but usually exceeded chicory crown temperature (stubble height by species interaction) (Tables 1 and 2). Only in the 115 mm stubble height treatment did tall fescue and chicory crown temperatures (75th percentile) not significantly differ from each other. In the 115 mm stubble height treatment, 90th percentiles of crown temperature did not significantly differ between species in any regrowth cycle (stubble height by species by regrowth cycle interaction) (Tables 1 and 3). In RC1 and RC2, 90th percentiles of crown temperature for perennial ryegrass seldom differed from tall fescue in the 35 mm and 55 mm stubble height treatments, but always exceeded chicory by ≥3.0˚C (stubble height by species by regrowth cycle interaction) (Tables 1 and 3). At the 90th percentile, crown temperatures for tall fescue and chicory in these stubble height treatments only differed in RC1, when tall fescue crown temperatures averaged 2.6˚C higher temperatures.

[Insert Table 2 and Table 3 near here]

### Growing season two

In the second growing season, an interaction between stubble height by species by regrowth cycle was observed on the 75th and 90th percentiles of crown temperature (Tables 1, 4 and 5). In each regrowth cycle, perennial ryegrass crown temperature (75th and 90th percentiles) for the 35 mm and 55 mm stubble height treatments did not significantly differ, but usually exceeded crown temperature under the 115 mm stubble height treatment. Across summer regrowth cycles (RC3-RC5), crown temperature differences averaged 3.1˚C for the 75th percentile, and 4.2˚C for the 90th percentile. In each regrowth cycle, tall fescue crown temperatures (75th and 90th percentiles) were usually higher under the 35 mm or 55 mm cf. 115 mm stubble height treatment. Tall fescue crown temperature (75th and 90th percentiles) was either equal or greater under the 35 mm compared to the 55 mm stubble height treatment. At the 75th percentile, chicory crown temperature was observed to be affected by stubble height in RC1, RC3 and RC5. In each of these regrowth cycles, chicory crown temperature under the 35 mm and 55 mm stubble height treatments were not significantly different, but exceeded crown temperature under the 115 mm treatment by 1.2-1.5˚C. Similar observations are made in RC1-RC4 for the 90th percentile of chicory crown temperature, with differences ranging between 1.3-2.5˚C. In both RC5 and RC6, chicory crown temperature (90th percentile) significantly differed between the 55 mm and 115 mm stubble height treatments, averaging 1.5˚C higher under the 55 mm stubble height treatment.

In each stubble height treatment, perennial ryegrass crown temperatures (75th and 90th percentiles) in most regrowth cycles equaled or exceeded tall fescue crown temperatures, and mostly exceeded chicory crown temperatures. In both the 35 mm and 55 mm stubble height treatments, tall fescue experienced higher crown temperatures than chicory in more regrowth cycles when comparisons are made at the 90th vs. 75th percentile. At the 90th percentile of crown temperature, tall fescue exceeded chicory by (i) 2.5-7.6˚C across RC1-RC5, 35 mm stubble height treatment; and (ii) 1.8-5.0˚C across RC1-RC3 and RC5, 55 mm stubble height treatment. In the 115 mm stubble height treatment, 75th and 90th percentiles of tall fescue crown temperature exceeded chicory in RC1 by 4.3˚C and 5.2˚C, respectively. In all other regrowth cycles, crown temperature of these two species seldom differed from each other.

[Insert Table 4 and Table 5 near here]

## Canopy leaf area index

Within each regrowth cycle, canopy LAI values for each species were always significantly lower under the 35 mm or 55 mm cf. 115 mm stubble height treatment (Fig. 4). In some regrowth cycles, canopy LAI values for both perennial ryegrass and tall fescue were significantly lower under the 35 mm vs. 55 mm stubble height treatment (Fig. 4).

[Insert Fig. 4 near here]

# Discussion

## Stubble height effects

Results demonstrate the potential of stubble height management to affect the crown temperature of three perennial pasture species. Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) increased the likelihood of perennial ryegrass, tall fescue, and chicory experiencing higher crown temperatures in the subsequent regrowth cycle (Tables 2-5). As our study was concerned with supraoptimal crown temperatures, only temperature increases at the upper end of the crown temperature distribution (75th and/or 90th percentiles) are reported. Across summer regrowth cycles of growing season two, defoliating to shorter stubble heights increased the 90th percentile of crown temperature by an average of 4.2˚C for perennial ryegrass, 3.6˚C for tall fescue, and 1.8˚C for chicory (Table 5). Observed crown temperature increases may be partially explained by the lower canopy LAI of swards defoliated to shorter stubble heights (Fig. 4), which we assume permitted more SR interception at the canopy base ([Harrison *et al.* 2015](#_ENREF_22)). Defoliating to lower stubble heights can also reduce the capacity of plants to dissipate excess heat via transpiration ([Harrison *et al.* 2011](#_ENREF_21)), with the potential cooling effect of transpiration being considerable ([Feldhake *et al.* 1984](#_ENREF_15); [Temple and Benoit 1988](#_ENREF_52); [Brown *et al.* 2004](#_ENREF_9)).

The upper distribution of perennial ryegrass and chicory crown temperatures (75th and 90th percentiles) seldom differed between swards defoliated to stubble heights of 35 mm vs. 55 mm (Tables 2-5). We assume defoliating to these contrasting stubble heights did not unduly affect SR interception at the canopy base of either species, or their transpiration capacity. By contrast, tall fescue defoliated to a stubble height of 35 mm vs. 55 mm had increased crown temperatures in half the regrowth cycles of growing season two. Crown temperature increases were evident at both the 75th and 90th percentiles, which were elevated by as much as 4.3˚C and 5.7˚C, respectively (Tables 4 and 5). Tall fescue swards defoliated to stubble heights of 35 mm vs. 55 mm often had lower canopy LAI values (when measured, see Fig. 4). While small in magnitude, these differences may have sufficiently affected levels of SR intercepted at the base of the tall fescue canopy to affect crown temperature.

Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) increased the summer-autumn growth of each species ([Langworthy *et al.* submitted](#_ENREF_29)). This result indicates supraoptimal crown temperatures either did not occur, or occurred for insufficient duration to have detrimentally affected potential growth ([Chen *et al.* 1982](#_ENREF_11)). We can confirm perennial ryegrass experienced periods of supraoptimal crown temperatures during summer regrowth cycles (>32˚C), even when defoliated to the 115 mm stubble height (Fig. 3). This supraoptimal threshold is derived from previous research, which manipulated temperature of the stem apex (location of shoot apex, apical meristem and growing points) at the crown ([Peacock 1975b](#_ENREF_42), [1975a](#_ENREF_41)). Stem apex temperatures >32˚C reduced the rate of perennial ryegrass leaf extension, which became negligible when stem apex temperatures reached 40˚C ([Peacock 1975b](#_ENREF_42)). When defoliated to stubble heights of 35 mm or 55 mm, perennial ryegrass summer crown temperatures in growing season two exceeded this threshold, being ≥35˚C for 2% of the total time, and on a few occasions reaching ~40˚C (Fig. 3). We suggest that supraoptimal crown temperatures occurred for insufficient duration to have detrimentally affected perennial ryegrass growth. It is unknown if tall fescue or chicory experienced supraoptimal crown temperatures as these thresholds appear undefined.

Results likely reflect what would normally be experienced at the experimental location (NW Tasmania), as both Ta and SR were close to long-term averages (1975-2014) (Fig. 2b, c). Therefore, it is unlikely defoliating to stubble heights of 35 mm or 55 mm in NW Tasmania would compromise growth of any examined species as a consequence of supraoptimal crown temperature stress. When interpreting presented results, the influence of environment as part of the genotype by environment by management interaction should not be ignored. The effect of defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) on crown temperature may negatively affect plant growth and survival in environments characterised by higher summer crown temperatures. Summers in these warmer environments would likely feature higher Ta and daily total SR levels than those experienced at the experimental site. The highest 90th and 75th percentiles of crown temperature were recorded during summer regrowth cycles (Tables 2-5), when maximum and minimum daily Ta peaked (Fig. 2a).

In warmer environments, detrimental effects of defoliating to shorter stubble heights may extend beyond elevating apical meristem temperature (located at the crown of vegetative plants) ([Rumball 1986](#_ENREF_47); [Korte *et al.* 1987](#_ENREF_28); [Yang *et al.* 1998](#_ENREF_57)). Defoliating to shorter stubble heights may also reduce availability of non-structural carbohydrate (NSC) plant reserves that support respiration during periods of supraoptimal temperature stress, and further accelerate their rate of depletion. During such periods, plants often utilise their NSC reserves to support respiration ([Sullivan and Sprague 1949](#_ENREF_50); [Alberda 1965](#_ENREF_2)), as supraoptimal temperatures increase rate of respiration but not photosynthesis ([White 1973](#_ENREF_55)). As the stubble is the primary NSC storage organ in grasses ([Fulkerson and Slack 1994](#_ENREF_16); [Donaghy *et al.* 2008](#_ENREF_13)), defoliating to stubble heights <40 mm reduces the NSC content of plants ([Lee *et al.* 2008](#_ENREF_32)). By elevating crown temperature, defoliating to shorter stubble heights may further increase respiration rates ([Murata and Iyama 1963](#_ENREF_39)), potentially exhausting available NSC reserves and culminating in plant death ([Sullivan and Sprague 1949](#_ENREF_50)).

Further research is required to confirm if defoliating to shorter stubble heights in these warmer environments results in crown temperatures that detrimentally affect plant growth and survival. If leaving higher stubble heights benefits summer growth, research is required to determine the effect of incremental increases in stubble height between 55 mm and 115 mm on crown temperatures. This is because leaving a stubble height of 115 mm for a single regrowth cycle may be a viable option for minimising the exposure of swards to short durations of supraoptimal crown temperature stress (e.g. heat waves), but continuing this practice over multiple regrowth cycles can reduce the growth and nutritive value of grazeable herbage ([Lee *et al.* 2007](#_ENREF_31); [Langworthy *et al.* submitted](#_ENREF_29)). An objective of the proposed research should be to identify stubble heights below 115 mm that effectively suppress crown temperature, while minimising abovementioned limitations.

## Species effects

When defoliated to the same stubble height, chicory and second year tall fescue swards experienced less extreme crown temperatures than perennial ryegrass swards. Across summer regrowth cycles of growing season two, 75th and 90th percentiles of perennial ryegrass crown temperatures were as much as 5.9˚C and 6.9˚C higher than chicory crown temperatures, respectively (Tables 4 and 5). The upper distribution of crown temperature seldom differed between perennial ryegrass and tall fescue in growing season one but differed in half the regrowth cycles of growing season two (Tables 2-5). When differences occurred in growing season two, perennial ryegrass generally experienced higher crown temperatures. In relevant summer regrowth cycles of growing season two, 75th and 90th percentiles of perennial ryegrass crown temperatures were ≥1.7˚C and ≥3.0˚C higher than tall fescue (Tables 4 and 5).

Chicory and tall fescue’s lower crown temperatures may contribute to their superior growth in environments with hotter summers than NW Tasmania (i.e. south-western and northern Victoria) ([Greenwood *et al.* 2006](#_ENREF_20); [Tharmaraj *et al.* 2008](#_ENREF_53); [Raeside *et al.* 2014](#_ENREF_43)). Potential advantages of maintaining cooler crown temperatures during hot summers include reducing the exposure of the apical meristem of vegetative plants to supraoptimal temperature stress ([Rumball 1986](#_ENREF_47); [Korte *et al.* 1987](#_ENREF_28); [Yang *et al.* 1998](#_ENREF_57)). Maintaining cooler crown temperatures may also be advantageous in limiting consumption of plant NSC reserves ([Sullivan and Sprague 1949](#_ENREF_50); [Murata and Iyama 1963](#_ENREF_39)). As discussed above, this would reduce the likelihood of plants exhausting NSC reserves, which results in plant death ([Sullivan and Sprague 1949](#_ENREF_50)).

Chicory and tall fescue are known to be more tolerant of supraoptimal temperature stress than perennial ryegrass ([Jiang and Huang 2001](#_ENREF_25); [Langworthy *et al.* 2018](#_ENREF_30)). [Jiang and Huang (2001)](#_ENREF_25) attributed the superior supraoptimal temperature tolerance of tall fescue *in situ* to the species greater transpirational cooling capacity than seen in perennial ryegrass. This is explained by the species deeper and more extensive root system, which enables tall fescue plants to access soil water stores at greater depth than perennial ryegrass. Whilst transpirational cooling is an important mechanism in maintaining lower plant temperatures ([Feldhake *et al.* 1984](#_ENREF_15); [Temple and Benoit 1988](#_ENREF_52); [Brown *et al.* 2004](#_ENREF_9)), it is unlikely transpiration differences fully explain the cooler crown temperatures of both tall fescue and chicory relative to perennial ryegrass. This is because similar soil water extraction patterns were observed for each species; see soil water content data presented in [Langworthy *et al.* (submitted)](#_ENREF_29). It is likely the canopy base of the chicory and tall fescue swards were more shaded from incoming SR limiting elevation of crown temperatures ([Harrison *et al.* 2015](#_ENREF_22)). This cannot be confirmed as LAI was only measured on a relative basis (i.e. only intraspecies comparisons can be made).

# Conclusion

Defoliating to shorter stubble heights (35 mm or 55 mm cf. 115 mm) increased the likelihood of perennial ryegrass, tall fescue, and chicory experiencing higher crown temperatures in subsequent regrowth cycles. Increases in crown temperature occurred at the upper end of the crown temperature distribution (75th and/or 90th percentiles). Defoliating to shorter stubble heights in NW Tasmania is unlikely to compromise growth as a result of supraoptimal crown temperatures. The cool-temperate climate of the experimental site would have limited the extent and duration of supraoptimal crown temperatures. Defoliating to shorter stubble heights may negatively affect plant growth and survival in environments featuring higher summer crown temperatures than the experimental site. Research is required to confirm this hypothesis. Chicory and second year tall fescue swards experienced less extreme crown temperatures than perennial ryegrass. This may partly contribute to the cited superior growth of these species in hotter summer environments than NW Tasmania.

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# Conflicts of interest

The authors declare no conflicts of interest.

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# Tables

**Table 1.** Significance levels for main-effects and interactions included in quantile regression analyses for the 75th and 90th percentiles of crown temperature. Each of two growing seasons (GS) were analysed separately. Wald tests for main-effects and interactions retained in refined models are presented. Abbreviations include: (i) degrees of freedom, DF; (ii) regrowth cycle, RC; (iii) species, S; and (iv) stubble height, SH.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  | **75th percentile** | |  | **90th percentile** | |
|  |  |  |  |  |  |  |  |  |
| **GS** | **Main-effect/interaction** | **DF** |  | **Chi-square value** | ***P*-value** |  | **Chi-square value** | ***P*-value** |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| 1 | SH | 2 |  | 47.8 | \*\* |  | 66.3 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | S | 2 |  | 4.1 | NS |  | 2.3 | NS |
|  |  |  |  |  |  |  |  |  |
|  | SH•S | 4 |  | 12.8 | \* |  | 26.6 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | RC | 2 |  | 445.8 | \*\* |  | 179.9 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | SH•RC | 4 |  |  |  |  | 9.5 | NS |
|  |  |  |  |  |  |  |  |  |
|  | S•RC | 4 |  | 68.6 | \*\* |  | 19.4 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | SH•S•RC | 8 |  |  |  |  | 28.7 | \*\* |
|  |  |  |  |  |  |  |  |  |
| 2 | SH | 2 |  | 17.8 | \*\* |  | 10.4 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | S | 2 |  | 38.1 | \*\* |  | 53.2 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | SH•S | 4 |  | 21.8 | \*\* |  | 17.8 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | RC | 5 |  | 106.5 | \*\* |  | 154.4 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | SH•RC | 10 |  | 63.2 | \*\* |  | 91.5 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | S•RC | 10 |  | 107.0 | \*\* |  | 112.5 | \*\* |
|  |  |  |  |  |  |  |  |  |
|  | SH•S•RC | 20 |  | 108.0 | \*\* |  | 78.4 | \*\* |
|  |  |  |  |  |  |  |  |  |

*P*-values, NS = non-significant (*P*≥0.05), \**P*<0.05, \*\**P*<0.01.

**Table 2.** Growing season one, 75th percentiles of crown temperature for perennial ryegrass, tall fescue, and chicory in each stubble height (SH) treatment and regrowth cycle (RC). Analysis was restricted to crown temperatures logged between 0800-1700 h (Australian eastern standard time). Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time-series adjusted values should only be used for statistical comparisons.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |
| **Interaction** |  |  | **Perennial ryegrass** | | **Tall fescue** | | **Chicory** | |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| SH by species | SH | 35 | **24.3** (0.42 ± 0.06) | Aa | **23.8** (0.45 ± 0.14) | Aa | **22.0** (0.36 ± 0.13) | Ab |
|  | (mm) | 55 | **24.0** (0.44 ± 0.06) | Aa | **23.6** (0.42 ± 0.14) | Aa | **21.8** (0.35 ± 0.13) | Ab |
|  |  | 115 | **22.2** (0.35 ± 0.03) | Ba | **22.1** (0.33 ± 0.09) | Bab | **21.1** (0.29 ± 0.08) | Bb |
|  |  |  |  |  |  |  |  |  |
| Species by RC | RC | 1 (summer) | **27.8** (0.56 ± 0.06) | Aa | **27.1** (0.57 ± 0.15) | Aa | **24.9** (0.43 ± 0.14) | Ab |
|  |  | 2 (summer) | **24.3** (0.41 ± 0.05) | Ba | **24.1** (0.39 ± 0.13) | Ba | **22.3** (0.32 ± 0.13) | Bb |
|  |  | 3 (autumn) | **18.4** (0.24 ± 0.03) | Ca | **18.4** (0.24 ± 0.09) | Ca | **17.6** (0.24 ± 0.08) | Ca |
|  |  |  |  |  |  |  |  |  |

Values followed by the same: (i) uppercase letter do not differ within a species (P≥0.05); and (ii) lowercase letter do not differ within a row (i.e. between species).

**Table 3.** For each regrowth cycle (RC) of growing season one, 90th percentiles of crown temperature are presented for perennial ryegrass, tall fescue, and chicory in each stubble height (SH) treatment. Analysis restricted to crown temperatures logged between 0800-1700 h (Australian eastern standard time). Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time-series adjusted values should only be used for statistical comparisons.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |
| **RC** | **Season** | **SH (mm)** | **Perennial ryegrass** | | **Tall fescue** | | **Chicory** | |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| 1 | summer | 35 | **30.8** (1.12 ± 0.11) | Aa | **29.5** (1.13 ± 0.09) | Aa | **27.5** (0.80 ± 0.06) | Ab |
|  |  | 55 | **30.9** (1.05 ± 0.13) | Ab | **30.3** (1.28 ± 0.09) | Aa | **27.2** (0.82 ± 0.06) | Ac |
|  |  | 115 | **28.7** (0.95 ± 0.09) | Aa | **27.9** (0.93 ± 0.10) | Ba | **26.2** (0.81 ± 0.05) | Aa |
|  |  |  |  |  |  |  |  |  |
| 2 | summer | 35 | **27.3** (0.90 ± 0.11) | Aa | **27.0** (0.89 ± 0.07) | Aab | **24.3** (0.77 ± 0.04) | Ab |
|  |  | 55 | **27.0** (0.82 ± 0.04) | Aa | **26.0** (0.79 ± 0.06) | Aab | **23.8** (0.65 ± 0.09) | ABb |
|  |  | 115 | **24.8** (0.65 ± 0.07) | Ba | **24.7** (0.65 ± 0.07) | Ba | **23.0** (0.56 ± 0.04) | Ba |
|  |  |  |  |  |  |  |  |  |
| 3 | autumn | 35 | **20.7** (0.49 ± 0.05) | ABb | **21.0** (0.64 ± 0.05) | Aa | **20.0** (0.65 ± 0.05) | Aa |
|  |  | 55 | **20.5** (0.58 ± 0.04) | Aa | **20.3** (0.56 ± 0.05) | Aa | **19.5** (0.53 ± 0.04) | Ba |
|  |  | 115 | **19.0** (0.39 ± 0.03) | Ba | **18.7** (0.39 ± 0.03) | Ba | **18.5** (0.42 ± 0.03) | Ca |
|  |  |  |  |  |  |  |  |  |

Values followed by the same: (i) uppercase letter do not differ within a RC by species combination (*P*≥0.05); and (ii) lowercase letter do not differ within a row (i.e. between species).

**Table 4.** For each regrowth cycle (RC) of growing season two, 75th percentiles of crown temperature are presented for perennial ryegrass, tall fescue, and chicory in each stubble height (SH) treatment. Analysis restricted to crown temperatures logged between 0800-1700 h (Australian eastern standard time). Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time-series adjusted values should only be used for statistical comparisons.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |
| **RC** | **Season** | **SH (mm)** | **Perennial ryegrass** | | **Tall fescue** | | **Chicory** | |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| 1 | spring | 35 | **21.7** (0.60 ± 0.05) | Aa | **22.3** (0.60 ± 0.09) | Aa | **17.0** (0.30 ± 0.03) | Ab |
|  |  | 55 | **21.7** (0.59 ± 0.05) | Aa | **20.8** (0.49 ± 0.08) | ABa | **16.8** (0.24 ± 0.03) | Ab |
|  |  | 115 | **19.5** (0.35 ± 0.05) | Ba | **19.8** (0.38 ± 0.04) | Ba | **15.5** (0.14 ± 0.03) | Bb |
|  |  |  |  |  |  |  |  |  |
| 2 | spring | 35 | **26.5** (0.70 ± 0.04) | Aa | **27.1** (0.78 ± 0.06) | Aa | **20.8** (0.31 ± 0.04) | Ab |
|  |  | 55 | **25.3** (0.63 ± 0.07) | Aa | **22.8** (0.35 ± 0.04) | Bb | **20.3** (0.29 ± 0.03) | Ab |
|  |  | 115 | **23.8** (0.37 ± 0.04) | Ba | **21.0** (0.24 ± 0.04) | Cb | **19.0** (0.22 ± 0.05) | Ab |
|  |  |  |  |  |  |  |  |  |
| 3 | summer | 35 | **28.5** (0.74 ± 0.09) | Aa | **26.8** (0.54 ± 0.08) | Ab | **23.5** (0.45 ± 0.04) | Ab |
|  |  | 55 | **28.8** (0.72 ± 0.07) | Aa | **25.3** (0.48 ± 0.07) | Ab | **23.5** (0.44 ± 0.04) | Ab |
|  |  | 115 | **26.2** (0.47 ± 0.06) | Ba | **23.5** (0.35 ± 0.03) | Bab | **22.3** (0.33 ± 0.03) | Bb |
|  |  |  |  |  |  |  |  |  |
| 4 | summer | 35 | **30.3** (0.77 ± 0.05) | Aa | **28.2** (0.64 ± 0.05) | Ab | **24.4** (0.42 ± 0.03) | Ac |
|  |  | 55 | **30.2** (0.74 ± 0.06) | Aa | **26.7** (0.46 ± 0.05) | Bb | **24.9** (0.43 ± 0.04) | Ab |
|  |  | 115 | **26.8** (0.45 ± 0.04) | Ba | **24.8** (0.33 ± 0.06) | Bb | **24.0** (0.36 ± 0.04) | Ab |
|  |  |  |  |  |  |  |  |  |
| 5 | summer | 35 | **28.2** (0.87 ± 0.07) | Aa | **27.2** (0.81 ± 0.06) | Aab | **25.0** (0.70 ± 0.04) | Ab |
|  |  | 55 | **28.7** (0.96 ± 0.10) | Aa | **26.2** (0.81 ± 0.05) | Aab | **25.0** (0.71 ± 0.05) | Ab |
|  |  | 115 | **25.0** (0.61 ± 0.04) | Ba | **23.8** (0.57 ± 0.07) | Ba | **23.7** (0.56 ± 0.06) | Ba |
|  |  |  |  |  |  |  |  |  |
| 6 | autumn | 35 | **23.9** (0.45 ± 0.05) | Aa | **23.0** (0.36 ± 0.03) | Aab | **21.7** (0.30 ± 0.03) | Ab |
|  |  | 55 | **23.3** (0.37 ± 0.04) | ABa | **22.7** (0.32 ± 0.03) | Aa | **22.2** (0.32 ± 0.03) | Aa |
|  |  | 115 | **22.8** (0.33 ± 0.03) | Ba | **21.0** (0.19 ± 0.03) | Bb | **21.5** (0.27 ± 0.03) | Aa |
|  |  |  |  |  |  |  |  |  |

Values followed by the same: (i) uppercase letter do not differ within a RC by species combination (P≥0.05); and (ii) lowercase letter do not differ within a row (i.e. between species).

**Table 5.** For each regrowth cycle (RC) of growing season two, 90th percentiles of crown temperature are presented for perennial ryegrass, tall fescue, and chicory in each stubble height (SH) treatment. Analysis restricted to crown temperatures logged between 0800-1700 h (Australian eastern standard time). Actual (unadjusted) crown temperature values are presented for biological meaning (referenced in-text), with time series adjusted crown temperature (°C) values ± 0.5 x 90% confidence interval in parenthesis. Time-series adjusted values should only be used for statistical comparisons.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |
| **RC** | **Season** | **SH (mm)** | **Perennial ryegrass** | | **Tall fescue** | | **Chicory** | |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| 1 | spring | 35 | **24.5** (1.15 ± 0.10) | Aa | **25.4** (1.27 ± 0.11) | Aa | **18.7** (0.69 ± 0.06) | Ab |
|  |  | 55 | **24.7** (1.13 ± 0.09) | Aa | **23.3** (1.05 ± 0.10) | Aa | **18.3** (0.52 ± 0.06) | Bb |
|  |  | 115 | **21.5** (0.76 ± 0.03) | Ba | **22.0** (0.79 ± 0.07) | Ba | **16.8** (0.37 ± 0.05) | Cb |
|  |  |  |  |  |  |  |  |  |
| 2 | spring | 35 | **29.5** (1.27 ± 0.08) | Ab | **30.8** (1.60 ± 0.23) | Aa | **23.2** (0.75 ± 0.07) | Ac |
|  |  | 55 | **28.3** (1.20 ± 0.08) | Aa | **25.1** (0.85 ± 0.03) | Bb | **22.2** (0.69 ± 0.06) | Ac |
|  |  | 115 | **26.2** (0.85 ± 0.08) | Ba | **22.8** (0.59 ± 0.06) | Cb | **20.7** (0.48 ± 0.07) | Bb |
|  |  |  |  |  |  |  |  |  |
| 3 | summer | 35 | **33.4** (1.36 ± 0.06) | Aa | **31.5** (1.20 ± 0.10) | Aa | **26.5** (0.91 ± 0.05) | Ab |
|  |  | 55 | **33.4** (1.32 ± 0.12) | Aa | **29.4** (1.11 ± 0.12) | Aa | **26.7** (0.87 ± 0.06) | Ab |
|  |  | 115 | **29.5** (0.91 ± 0.07) | Ba | **26.5** (0.68 ± 0.06) | Bb | **25.2** (0.66 ± 0.09) | Bb |
|  |  |  |  |  |  |  |  |  |
| 4 | summer | 35 | **34.1** (1.24 ± 0.04) | Aa | **31.3** (1.14 ± 0.17) | Aa | **28.8** (0.79 ± 0.05) | Ab |
|  |  | 55 | **33.4** (1.26 ± 0.05) | Aa | **29.3** (0.85 ± 0.07) | Bb | **28.5** (0.81 ± 0.07) | Ab |
|  |  | 115 | **29.2** (0.79 ± 0.03) | Ba | **27.0** (0.66 ± 0.06) | Cab | **26.3** (0.63 ± 0.03) | Bb |
|  |  |  |  |  |  |  |  |  |
| 5 | summer | 35 | **32.0** (1.69 ± 0.06) | Aa | **30.8** (1.56 ± 0.19) | Aa | **28.3** (1.24 ± 0.07) | ABb |
|  |  | 55 | **32.3** (1.76 ± 0.12) | Aa | **30.5** (1.55 ± 0.12) | Aa | **28.7** (1.30 ± 0.05) | Ab |
|  |  | 115 | **28.0** (1.18 ± 0.07) | Ba | **27.2** (1.05 ± 0.15) | Ba | **27.0** (1.09 ± 0.14) | Ba |
|  |  |  |  |  |  |  |  |  |
| 6 | autumn | 35 | **27.4** (0.92 ± 0.10) | Aa | **26.1** (0.79 ± 0.06) | Aab | **24.7** (0.67 ± 0.06) | ABb |
|  |  | 55 | **26.3** (0.81 ± 0.04) | ABa | **25.5** (0.66 ± 0.04) | Bb | **25.0** (0.70 ± 0.03) | Aab |
|  |  | 115 | **25.3** (0.74 ± 0.05) | Ba | **23.2** (0.50 ± 0.04) | Cb | **23.7** (0.57 ± 0.04) | Bb |
|  |  |  |  |  |  |  |  |  |

Values followed by the same: (i) uppercase letter do not differ within a RC by species combination (*P*≥0.05); and (ii) lowercase letter do not differ within a row (i.e. between species).

# Figures

Growing season 2

RC1

RC2

RC3

RC4

RC5

RC6

RC3

RC2

RC1

Growing season 1

Stubble height treatments imposed

Irrigated establishment

Sown

D

D1

D2

D3

D4

D5

D6

D7

D8

D9

D10

D11

D12

D13

Crown temperature & LAI measured

LAI measured

Crown temperature measured

77d

39d

29d

35d

43d

55d

63d

50d

28d

30d

26d

28d

35d

35d

Sep.

Dec.

Jan.

Feb.

Mar.

Apr.

May.

Jun.

Jul.

Aug.

Sep.

Oct.

Nov.

Dec.

Jan.

Feb.

Mar.

Apr.

**2015**

**2016**

**2017**

**Fig. 1.** Schematic of the experimental sequence. Abbreviations include: (i) defoliation, D; (ii) regrowth cycle (RC), including regrowth cycles one to six (RC1 to RC6); and (iii) leaf area index, LAI.



**Fig. 2.** Eleven-day moving-average for maximum (▬▬) and minimum (▬▬) daily ambient temperature (*a*) during the experiment. Mean climatic data for each calendar month of the experiment (E) is presented with long-term (LT) means (1975-2014) for (*b*) maximum [E (●); LT (▬▬)] and minimum [E (▲); LT (▪ ▪ ▪ ▪)] daily ambient temperatures, and (*c*) total daily solar radiation [E (●); LT (▬▬)].



**Fig. 3.** Number of logged summer hours when crown temperature was ≥30˚C. Crown temperature was logged over multiple regrowth cycles including RC1 and RC2 for growing season one, and RC3-RC5 for growing season two. Crown temperature was logged for a total of 1200 hours (50 days) in growing season one, and 1824 hours (76 days) in growing season two. Values are means ± one standard error of the mean*.*



**Fig. 4.** Relative canopy leaf area index (LAI) of perennial ryegrass, tall fescue, and chicory swards in each stubble height treatment. Growing season one (GS1) and two (GS2) are graphed separately. Regrowth cycles (RC) where: (i) stubble height was only significant (P<0.05) as a main-effect feature a single point for each stubble height treatment; and (ii) stubble height by measurement time interaction was significant are shown as a line series, with a point for each measurement time. Values are least square means ± one standard error of the mean. Swards defoliated to stubble heights of 35 mm or 55 mm always had significantly lower canopy LAI values than those defoliated to a 115 mm stubble height. An asterisk (\*) signifies canopy LAI values were significantly lower under the 35 mm vs. 55 mm stubble height treatment.