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Evaluating seasonal risk and the potential for windspeed reductions to reduce chill index at six locations using GrassGro®

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Short Title: Evaluating seasonal risk to reduce chill index levels

Abstract

The death of new born lambs is a major factor influencing the reproductive efficiency of sheep enterprises. Adverse weather conditions (wind, precipitation and low temperature) either alone or in combination (chill index), can increase the level of new born lamb mortality to over 50% of births for short periods through increased heat loss. The provision of shelter to reduce wind speed and therefore chill index (heat loss) has been shown to reduce lamb mortality; however the reduction in mortality has been variable. This study used the decision support tool GrassGro® to determine the likelihood of adverse weather conditions occurring at six locations across south- eastern Australia which varied widely in climate. Data were extracted for 24 consecutive weekly periods between May and October over 39 years (1968-2006) to evaluate daily precipitation, temperature, radiation, wind speed and chill index. The minimum, maximum and median values were calculated for all climatic factors for every week and year combination. The effectiveness of reducing wind speed to reduce the occurrence of a high chill index was also evaluated. The severity of these weather events varied between locations with the median weekly chill index rarely exceeding 1000 kJ/m^2.hr at Temora, but at both Hamilton and Orange this occurred in over two thirds of the weeks examined. Reducing wind speed by 50% reduced the number of weeks with a median chill index exceeding 1000 kJ/m^2.hr in twice as many weeks at Hamilton and Yass compared with Orange. These results show that the potential for shelter to reduce chill index will vary according to the location and time of year. In locations where another climatic factor, such as low temperature or rainfall, has a greater influence on the chill index, shelter which only reduces wind speed, will be less effective than at locations where wind speed is the driver of chill index.

Keywords: lamb survival, weather, chill index, shelter

Introduction

The major cause of reproductive inefficiency is perinatal lamb mortality, with Australian studies showing pre-weaning mortality of lambs to range from 11 to 39% of births (Fogarty 1972; Knight *et al.* 1975; Donnelly 1984; Owens *et al.* 1985; Hatcher *et al.* 2009). The first 72 hours after birth are the critical time period for lamb survival to weaning (Haughey 1981; Miller 1991) with Scales *et al*. (1986) stating that 94% of lamb deaths were within this period.

Animal factors such as breed (Atkins 1980), ewe age, weight and condition (Alexander *et al.* 1993; Hatcher *et al.* 2009; Behrendt *et al.* 2011) and lamb birth weight or sex (Hight and Jury 1970; Hatcher *et al.* 2009) influence the level of perinatal mortality, as do various management factors such as stocking rate (Watson *et al.* 1968; Ferguson 1982; Robertson *et al.* 2011). Climatic factors can also be of major importance (Donnelly 1984). Poor weather (high winds and rain) during lambing can cause a marked increase in lamb deaths, in some cases exceeding 90% (Obst and Day 1968; Egan *et al.* 1972).

Climatic factors (temperature, wind speed, rainfall and solar radiation) affect lamb mortality by influencing the amount of heat loss from animals (Mount and Brown 1983). Warm blooded animals have an ambient temperature range within which they can maintain their body temperature. When exposed to temperatures lower than this range ("lower critical temperature") the animal's heat production needs to increase to maintain their body temperature. This temperature can be as low as -20^{o}C for adult sheep in full wool or, as high as 37^{o}C for a young lamb, depending upon its weight and age (Alexander 1974; Slee 1979). The lower critical temperature for lambs is higher as they are born wet, have low energy reserves and large surface to volume ratio (Alexander 1974; Bird *et al.* 1984; Freer *et al.* 2007). Below this temperature lambs can maintain their body temperature by increasing heat production by up to 500% of the base level. This maximum heat production or summit metabolism is approximately 1100 kJ/m^{2}.hr but can only be maintained for a few hours (Alexander 1962).

In Australia sheep generally graze on pastures throughout the year, including during lambing time (Brien *et al.* 2010). Under these extensive grazing conditions, any shelter present will provide protection from wind only and not rain. Shelter may be in the form of rows of trees (Egan *et al.* 1972), shrubs (Robertson *et al.* 2011) or various grass species (Egan *et al.* 1976; Alexander *et al.* 1980; McCaskill 2007).

The reduction in wind speed provided by shelter varies between different shelter types and locations. This depends upon several factors which include shelter height, porosity and the angle of the wind (Cleugh 2003). Wind speed reductions at a leeward distance equivalent to the height of the shelter ranged from 0 – 82% in various types of tree rows (Bird *et al.* 2007) and up to 90% for tall wheat grass (McCaskill 2007). The level of windspeed reduction decreases as the distance from the shelter increases (Bird 1998). When winds are not perpendicular to the shelter then the reduction in wind speed for a specific distance is reduced compared to when the wind is perpendicular to the shelter (Cleugh 2003).

The provision of shelter to reduce wind speed, thereby reducing the chill index, has been shown to reduce the level of mortality compared with unprotected single and twin lambs by between 3 - 13% (singles) and 14 – 37% (twins) of lambs born (McLaughlin *et al.* 1970; Egan *et al.* 1972; Egan *et al.* 1976; Lynch and Alexander 1977; Alexander *et al.* 1980; Bird *et al.* 1984). The establishment and maintenance of shelter however, can be expensive, with McEachern and Sackett (2008) estimating that it would cost $14100 to protect a 20 ha paddock with trees. Furthermore, the potential for shelter to reduce the chill index and increase lamb survival will depend on both the effectiveness of the shelter, and the risk of adverse weather conditions, which is further dependent on the locality and time of year when lambing occurs.

This study aimed to assess the risk of poor weather occurring during lambing by defining the probabilities of adverse weather events occurring during 24 consecutive weekly periods at several locations (Armidale, Hamilton, Orange, Tarcutta, Temora and Yass) in south-east Australia. The potential for a reduction in wind speed to reduce the chill index at these locations was also evaluated.

Materials and Methods

Historical weather conditions were modelled using GrassGro® (version 3.0.5) (Donnelly *et al.* 1997), a decision support tool developed by CSIRO. Wind chill or chill index can be calculated using several methods (Mount and Brown 1983; Osczevski 1995) with GrassGro® using the formula developed by Nixon-Smith (1972) for sheep graziers alerts issued by the Australian Bureau of Meteorology and modified by Donnelly (1984). This formula calculates the potential heat loss (C) in $kJ/m^2.hr$ using mean daily wind velocity (v; m/sec), the mean daily temperature (T; ^oC) and daily rainfall (x; mm) as shown below:

$$C = (11.7 + 3.1v^{0.5})(40-T) + 481 + (418(1-e^{-0.04x}))$$

Six locations across south-eastern Australia were selected to encompass a range of different climates: Armidale (30°31'S, 151°40'E, 980m elevation), Orange (33°23'S, 149°07'E, 948m) Tarcutta (35°17'S, 147°44'E, 232m), Temora (34°24'S, 147°32'E, 270m) and Yass (34°50'S, 148°55'E, 520m) in New South Wales and Hamilton (37°50'S, 142°04'E, 200m) in Victoria. Tarcutta was chosen as experimental work investigating the effects of shelter on lamb survival has recently been reported (Robertson *et al.* 2011), while the effects of shelter on survival have been extensively studied at Armidale (Alexander *et al.* 1980; Lynch *et al.* 1980) and Hamilton (McLaughlin *et al.* 1970; Egan *et al.* 1976). Orange and Yass were chosen as locations which often experience high chill indices (weekly maximum >1100 $kJ/m^2.hr$), while Temora was chosen as a location which rarely experiences such chill indices. Data for the 39 year period from 1968 to 2006 were used, 1968 being the earliest date at which weather data were available for all of the selected locations. While it is acknowledged anemometers are subjected to short-term biases (for example due to bearings sticking prior to lubrication), using records over 39 years reduces the impact of any such biases on the interpretation of the results. The potential effect of unprotected or sheltered lambing conditions was simulated by reducing recorded wind speeds by a range between 5 and 100%. While it is acknowledged that shelter may provide other benefits leading to improvements in lamb survival (eg ewe nesting or lamb behaviour), the current analysis does not account for these potential effects and focuses on chill index. Similarly, we assume shelter provides no measurable effect on components of chill index other than wind speed, namely temperature and precipitation.

For each location, weather data was extracted for seven day intervals between May 1 and October 15, providing 24 weekly periods per location. This timeframe was selected as this covers the time when lambing commonly occurs (Croker *et al.* 2009), and when climatic conditions with higher chill indices are most likely to occur. For each seven day period data were compiled for the daily precipitation, minimum and maximum temperature, solar radiation, wind speed and chill index. From this data the weekly minimum, maximum and median values were calculated for each parameter. The percentage of years these values exceeded specific thresholds were then calculated. The thresholds selected were a wind speed of 8 km/hr (Obst and Day 1968), a minimum temperature of below $0^{o}C$, a maximum temperature of below $10^{o}C$ (Alexander 1962) or a chill index of greater than 1000 and 1100 $kJ/m^2.hr$ (Alexander 1962; Kleemann and Walker 2005). Maximum values showed the thresholds were exceeded on one or more days of the week, minimum values showed they were exceeded on every day while the median value showed they were exceeded on four of the seven days providing a high likelihood (but not certainty) that this occurred on two or more consecutive days.

Obst and Evans (1970) suggested that reducing wind speed to below 8 km/hr for the six hours after birth would reduce lamb deaths by 8-15% annually over a 10 year period on Kangaroo Island. Alexander (1962) stated that at temperatures below $10^{o}C$

many wet lambs were unable to maintain their body temperature, with heat production lowest in lambs from ewes with lower pre-natal nutritional regimes.

Summit metabolism for a 5kg lamb is approximately 1100 kJ/m^2.hr and this can be maintained for only a few hours (Alexander 1962), therefore any chill index above that level can be detrimental to lamb survival. Kleemann and Walker (2005) found that, in conjunction with body weight, twin lamb survival was also correlated to the number of days the chill index exceeded 1000 kJ/m^2.hr. A median weekly chill index greater than 1000 kJ/m^2.hr indicates that at least four of the seven days exceed this level. In this situation many lambs could be exposed to two or three days of critical chill index levels in the critical period for lamb survival, the first 72 hours after birth (Haughey 1981). Reducing the median weekly chill index to below 1000 kJ/m^2.hr reduces the likelihood of lambs experiencing conditions of high chill index in this time period. The reduction of the maximum weekly chill index below 1100 kJ/m^2.hr or the median weekly chill index below 1000 kJ/m^2.hr are therefore important thresholds for lamb survival.

To examine the influence that reductions in wind speed had on chill index, for different levels of wind speed reduction, the number of years that the maximum chill index exceeded 1100 kJ/m^2.hr as a percentage of the number of years this occurred with no wind speed reduction was calculated for each of the 24 weeks at each location. The 24 weeks were then considered replicates and the data were analysed by two-way analysis of variance using Genstat® 11.1 (GenStat 2008).

Results

Likelihood of extreme weather events

The mean chill index for the period simulated (May 1 to October 15) was greater than 1100 kJ/m^2.hr at Hamilton, Orange, and Yass, while for the other locations it was below this threshold. While the mean maximum wind speed was higher at Tarcutta it was only at Hamilton and Yass that the mean wind speed was greater than 4 km/hr. Armidale, Orange and Yass all had mean minimum temperatures below 0^{o}C and the lowest minimum temperatures while Orange was the only location where the mean maximum temperature was less than 10^{o}C and the lowest maximum was below 0^{o}C (Table 1). Radiation was closely related to the latitude of the location, the further north the higher the radiation readings (data not shown).

Insert Table 1 here

Climatic factors exceeding critical levels at each location

At Armidale and Temora median wind speed exceeded 8 km/hr in less than 25% of years across all weeks (May to October), while at Tarcutta median wind speed exceeded 8km/hr in 25% of years for one week (August 21) only. At Hamilton, however, median wind speed was greater than 8 km/hr in more than 60% of years for all weeks, and for some weeks this occurred every year. At Yass and Orange median wind speeds exceeded 8 km/hr in over 25% of the years for more than half of the weeks examined (Fig. 1).

Median minimum temperatures rarely fell below 0^{o}C for any week at Hamilton, but at all other locations this occurred in more than 20% of years for some weeks (Fig. 1). At Orange the median maximum temperature did not reach 10^{o}C for 15 of the 24 weeks analysed in at least 10% of years; Yass was the only other location where this occurred in more than one week (Fig. 1). Median radiation levels below 8 MJ/m^2 were never observed at Armidale and only at Hamilton did this occur in more than 40% of years for any week.

Insert Fig. 1 here

At Tarcutta, Armidale and Temora the median chill index rarely exceeded 1100 kJ/m^2.hr for each week analysed and never for more than three percent of years analysed. At Orange it exceeded this level in more than 20% of years for one third of the weeks analysed while at Hamilton this only occurred in two weeks. The median chill index exceeded 1100 kJ/m^2.hr in 10% of years for 14 weeks at Orange, ten weeks at Hamilton and three weeks at Yass (Fig. 2). The median chill index exceeded 1000 kJ/m^2.hr in over 50% of years for more than half of the analysed weeks at Hamilton (20 weeks), Orange (17 weeks) and Yass (13 weeks) while it exceeded this threshold in 50% of years for one time period at Armidale and no weeks at Tarcutta or Temora (Fig. 2).

Only on three occasions was the minimum weekly chill index (all seven days) greater than 1100 kJ/m^2.hr, once at Hamilton and twice at Orange. At Temora the minimum weekly chill index was less than 1000 kJ/m^2.hr for all weeks analysed, while at Armidale and Tarcutta minimum chill index exceeded 1000 kJ/m^2.hr in less than half the weeks analysed and at both locations was an uncommon occurrence (less than 20% of years for these weeks). At Yass, Hamilton and Orange minimum chill indices exceeding 1000 kJ/m^2.hr were recorded in more than 75% of weeks and for many of these weeks this occurred in at least 10% of years (Fig. 2).

Hamilton, Orange and Yass were the locations at which the weekly median chill index most commonly exceeded both 1000 and 1100 kJ/m^2.hr. Orange was the location with the greatest overall incidence of the weekly median chill index exceeding 1100 kJ/m^2.hr (12% of instances) followed by Hamilton (8%), while it occurred least at Temora and Tarcutta (<1%). A weekly median chill index of greater than 1000 kJ/m^2.hr occurred most at Hamilton (72%) and Orange (67%) and least at Temora (6%).

Insert Fig. 2 here

Rainfall

At all locations there were years when rain was recorded on all seven days in a week. Hamilton and Orange were the only locations where this occurred in more than 10% of the years for more than one week. At these two sites for the 24 weeks simulated this level was exceeded for 19 and 11 of the weeks respectively. Rain was recorded on a minimum of four of the seven days at Hamilton in at least 50% of years for all weeks, at Orange at least 30%, Temora 15% and Yass 10%, while at both Tarcutta and Armidale it occurred in at least 10% of years for all but one week.

Influence of reducing wind speed

The effect of reducing wind speed was more important at some locations than others in terms of reducing the percentage of years with median chill index exceeding 1100

$kJ/m^2.hr$. At Armidale, Tarcutta and Temora the percentage of years in which the median weekly chill index exceeded 1100 $kJ/m^2.hr$ without reducing wind speed was low in all weeks analysed (Fig. 2). As such, reducing wind speed had minimal ability to influence the percentage of years with a median weekly chill index greater than 1100 $kJ/m^2.hr$ (Fig. 3). At the other locations this occurred in more weeks and on more occasions per week, with Hamilton recording a median weekly chill index for the week of more than 1100 $kJ/m^2.hr$ in a percentage of years for 21 of the 24 weekly periods, Orange in 18 and Yass in 16 weeks. At these locations, for those weeks, a 50% reduction of wind speed resulted in a 50% or greater reduction of the probability of the median chill index exceeding 1100 $kJ/m^2.hr$ in all weeks at Hamilton and all but two weeks at Orange and one at Yass (Fig. 3). The time when wind speed reductions were most effective varied between these locations, occurring earliest in Hamilton (mid-June to mid-August) and latest in Orange (late July to September) with Yass between these two locations (July to early August) (Fig. 3).

A 50% reduction in wind speed reduced the likelihood of the median weekly chill index exceeding 1000 $kJ/m^2.hr$ by greater than 50% in more than three quarters of the weeks in which it occurred at all sites except for Orange. At Orange the reduction exceeded 50% in only nine of the 24 weeks (Fig. 4)

Insert Fig. 3 here

Insert Fig. 4 here

A 10% reduction in wind speed provided a significant reduction in the probability of the maximum chill index exceeding 1100 $kJ/m^2.hr$ at all sites except Orange and Yass.

At these sites, a 15% reduction in wind speed was needed to significantly reduce the probability of maximum chill index exceeding 1100 kJ/m^2.hr (Fig. 5).

Insert Fig. 5 here

Discussion

The results from this study show that the risk of adverse weather and the potential for shelter to reduce chill index and therefore newborn lamb mortality varies according to the location. Where shelter can achieve a 100% reduction in wind speed the percentage of years where median weekly chill index exceeds 1000 kJ/m^2.hr during key lambing months is reduced to insignificant levels across all locations. Even at locations with a lower incidence of adverse chill index and wind speeds (eg. Armidale and Tarcutta), minor reductions (10%) in wind speed resulted in a significant reduction in the risk of high chill index occurring (Fig. 5). For some locations (Hamilton, Orange and Yass), however, even a 50% reduction in wind speed could not remove a significant risk of high chill index between June and September (Fig. 4).

In environments that have a low risk of a chill index greater than 1000 kJ/m^2.hr (similar to Temora), the cost of providing shelter may out-weigh any financial benefit gained from improved lamb survival. In this type of environment, changing lambing time to June or September would reduce most of the risk of high chill indices. In contrast, all other locations investigated in this study have limited potential to mitigate the risk of high chill indices through changing lambing time, unless lambing was to occur in May or October. Changing lambing time is likely to have significant implications on the productivity and supplementary feeding requirements of sheep enterprises, due to a less optimal alignment of pasture availability and flock feed requirements. These effects, plus potential reductions in ewe fertility (due to joining during seasonal anoestrous) and fecundity (ovulation rate peaks mid breeding season) (Lindsay 1988) should be considered against any benefits gained from increased lamb survival.

Shelter appears most effective in reducing lamb mortality during late winter-early spring. The probability of precipitation on a minimum of four days during these weeks was not markedly different compared to mid winter. At four sites (Tarcutta, Hamilton, Yass and Orange) the likelihood of median weekly wind speed exceeding 8 km/hr increased from late August. Furthermore, major decreases in the probability of the median weekly chill index exceeding 1100 $kJ/m^2.hr$ did not occur until late September at all locations (Fig. 2). If, as suggested by Obst and Evans (1970), mortality is significantly lower when wind speeds are below 8 km/hr then shelter may be of greater benefit for late winter or early spring lambing, which coincides with the peak time of lambing for many locations including Hamilton, Yass and Orange (Croker *et al.* 2009).

Much of the Australian research conducted on the ability of shelter to reduce new born lamb mortality has been conducted at Armidale (Alexander and Lynch 1976; Lynch and Alexander 1976; Alexander *et al.* 1980; Lynch *et al.* 1980). While these studies showed significant increases in lamb survival with shelter, other effects of shelter, such as increased pasture production (Bird *et al.* 1992) or greater privacy for lambing ewes (Alexander *et al.* 1983), rather than the reduction in windspeed *per se* may have contributed to the observed increases in survival. Given the present study shows the likelihood of extreme chill indices was lower at Armidale than other locations (Hamilton, Orange and Yass) (Table 1, Fig 2), this suggests the earlier studies may have underestimated the value of shelter directly on lamb survival at locations where extreme wind dependent chill indices are more likely to occur.

At Hamilton, Yass and Orange reductions in wind speed were equally effective in decreasing the likelihood of a median weekly chill index above 1100 kJ/m^2.hr (Fig. 4), but at Orange reductions in wind speed were less effective in decreasing the likelihood of the median weekly chill index exceeding 1000 kJ/m^2.hr (Fig. 5). This indicates that while wind speed may have a major influence in raising the chill index above 1100 kJ/m^2.hr at Orange it has a lesser role in causing a chill index between 1000 and 1100 kJ/m^2.hr (Fig. 5), when it is the increased likelihood of low minimum and maximum daily temperatures, combined with precipitation that drives the chill index.

While the levels of solar radiation appeared to be related mainly to latitude, its role in chill index should be acknowledged, in both its effect on warming and the reduction in warming from the wind (Brown and Mount 1987). Lower daily maximum temperatures are associated with cloudy days as downward solar radiation is reduced through clouds reflecting sunlight (Dai *et al.* 1999). At a location such as Orange where there was a high likelihood of a median daily maximum below 10^{o}C (most likely associated with cloudy days), the use of shelter to reduce wind speed to maximise the influence of low solar radiation levels, would be of importance in the survival of some newborn lambs.

Conversely minimum temperatures below $0^{o}C$ are normally associated with clear nights, low winds and radiation frosts (Bureau of Meteorology 2009). The reduction or elimination of wind, even at low speed, optimises the efficiency of solar radiation in warming a newborn lamb to above the lower critical temperature.

The consistency of wind direction can also influence the effectiveness of shelter. Shelter is less effective when not orientated perpendicular to the wind but can give good shelter at up to 30^{o} of the perpendicular (Cleugh 2003). Unless shelter belts entirely surround the area of concern, the possibility exists that adverse winds may prevail from an unprotected area resulting in GrassGro® overestimating the reduction in chill index levels due to shelter.

This paper has not investigated any other benefits of shelter to the producer. Animal and pasture production may be increased (Alexander and Lynch 1976; Bird 1998) and there is the potential` for the shelter to be used to reduce sheep deaths after shearing (Bird *et al.* 1984) or at other times of the year. Additionally, the planting of trees for shelter may have positive environmental impacts such as reducing dryland salinity (Schofield 1992).

This study has shown that location, the consequent climatic conditions and time of lambing are major factors that determine the effectiveness of shelter for the survival of new born lambs. The probability of poor weather occurring during lambing and the potential for a reduction in wind speed to reduce the chill index at a particular location and lambing time should be considered prior to investment in shelter.

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Table 1: Mean, minimum and maximum readings for maximum daily chill index (kJ/m^2.hr), maximum daily wind speed (km/hr) and lowest daily minimum and maximum temperature (^{o}C) for 24 weekly periods at six locations over 39 years (1968-2006).

Site	Chill index			Wind speed			Min temperature			Max temperature		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Armidale	1054.0	830.9	1397.1	2.69	0.02	11.32	-1.16	-9.30	10.00	12.23	3.00	24.60
Hamilton	1128.9	941.5	1433.7	4.52	1.61	14.80	1.59	-5.40	10.00	11.38	5.80	22.20
Orange	1150.7	905.7	1448.3	3.49	0.86	14.09	-0.99	-7.10	8.50	8.45	-0.20	21.40
Tarcutta	1075.5	870.0	1434.4	3.12	0.59	20.95	0.55	-6.28	10.50	12.89	5.00	23.51
Temora	1031.0	825.2	1338.9	2.09	0.36	11.49	0.41	-6.60	12.40	13.09	4.40	25.40
Yass	1109.3	889.0	1385.9	4.17	0.66	10.87	-0.90	-8.80	8.80	11.30	1.80	23.60

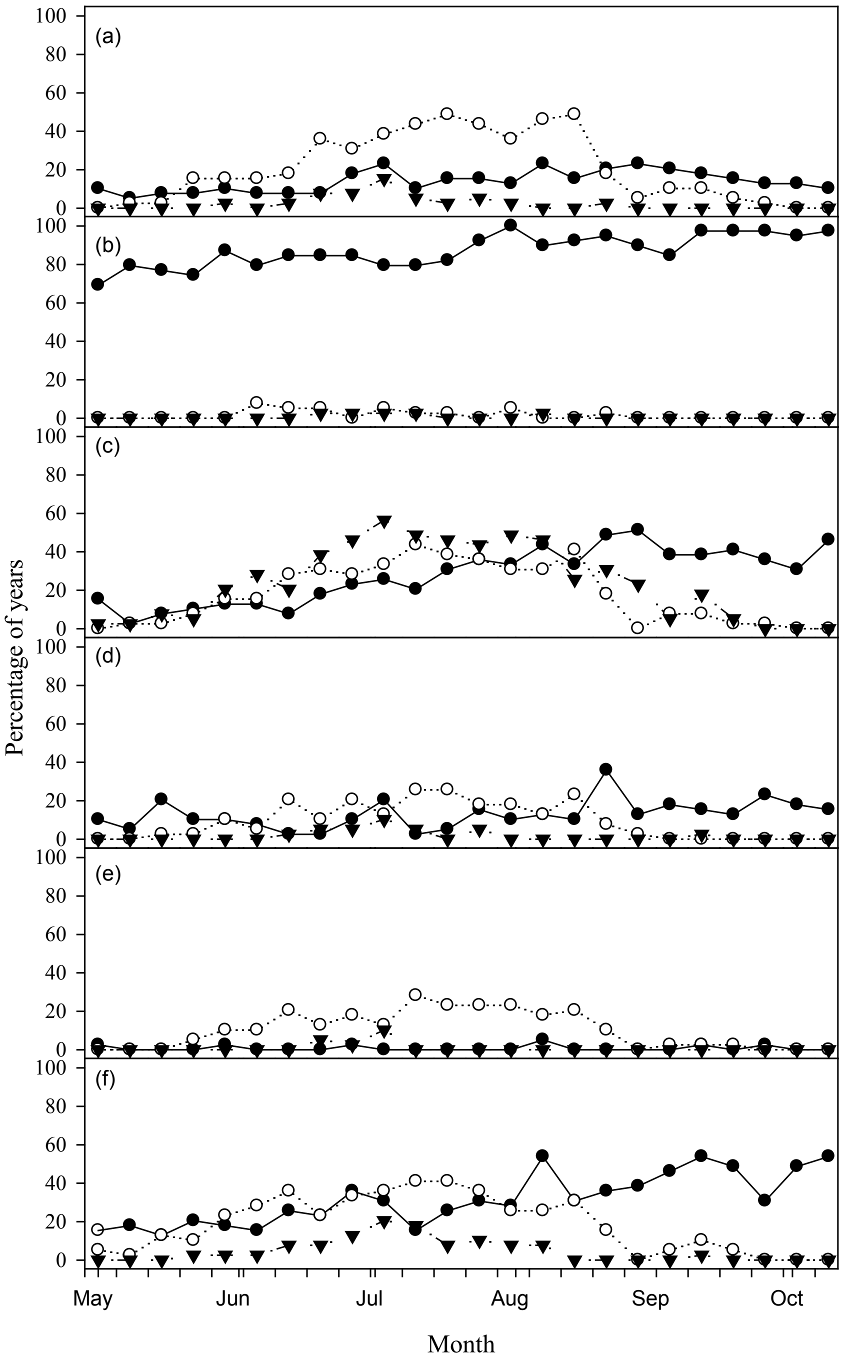

Figure 1: Likelihood of median weekly wind speed exceeding 8km/hr (–●–), minimum temperature below 0°C (○) or maximum temperature below 10 °C (--▼--) during 24 weekly periods from May to October at Armidale (a), Hamilton (b), Orange (c), Tarcutta (d), Temora (e) and Yass (f).

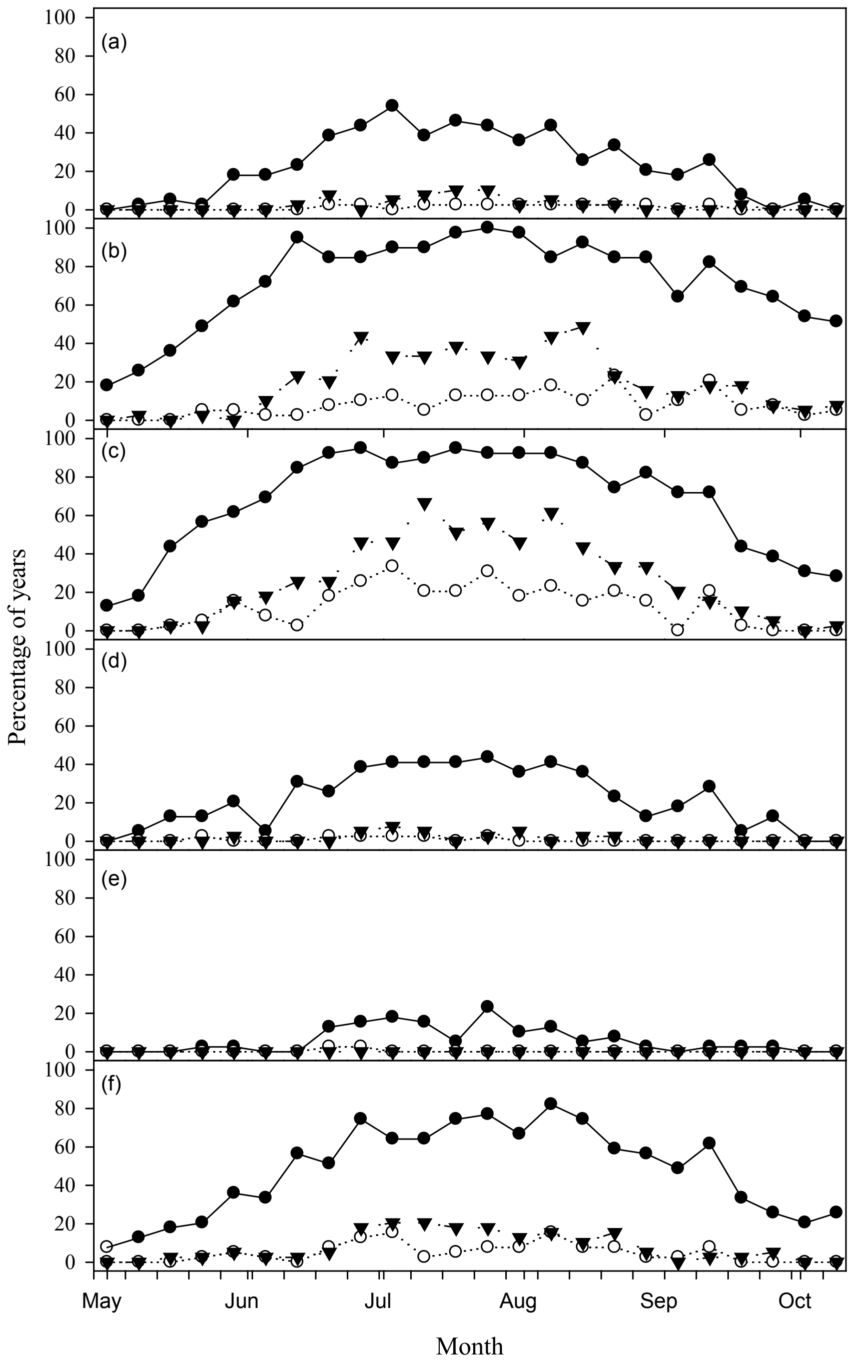

Figure 2: Likelihood of median chill index exceeding 1000 (—●—) and 1100 (○) kJ/m^2.hr and minimum chill index exceeding 1000 (--▼--) kJ/m^2.hr for 24 weekly periods from May to October at Armidale (a), Hamilton (b), Orange (c), Tarcutta (d), Temora (e) and Yass (f).

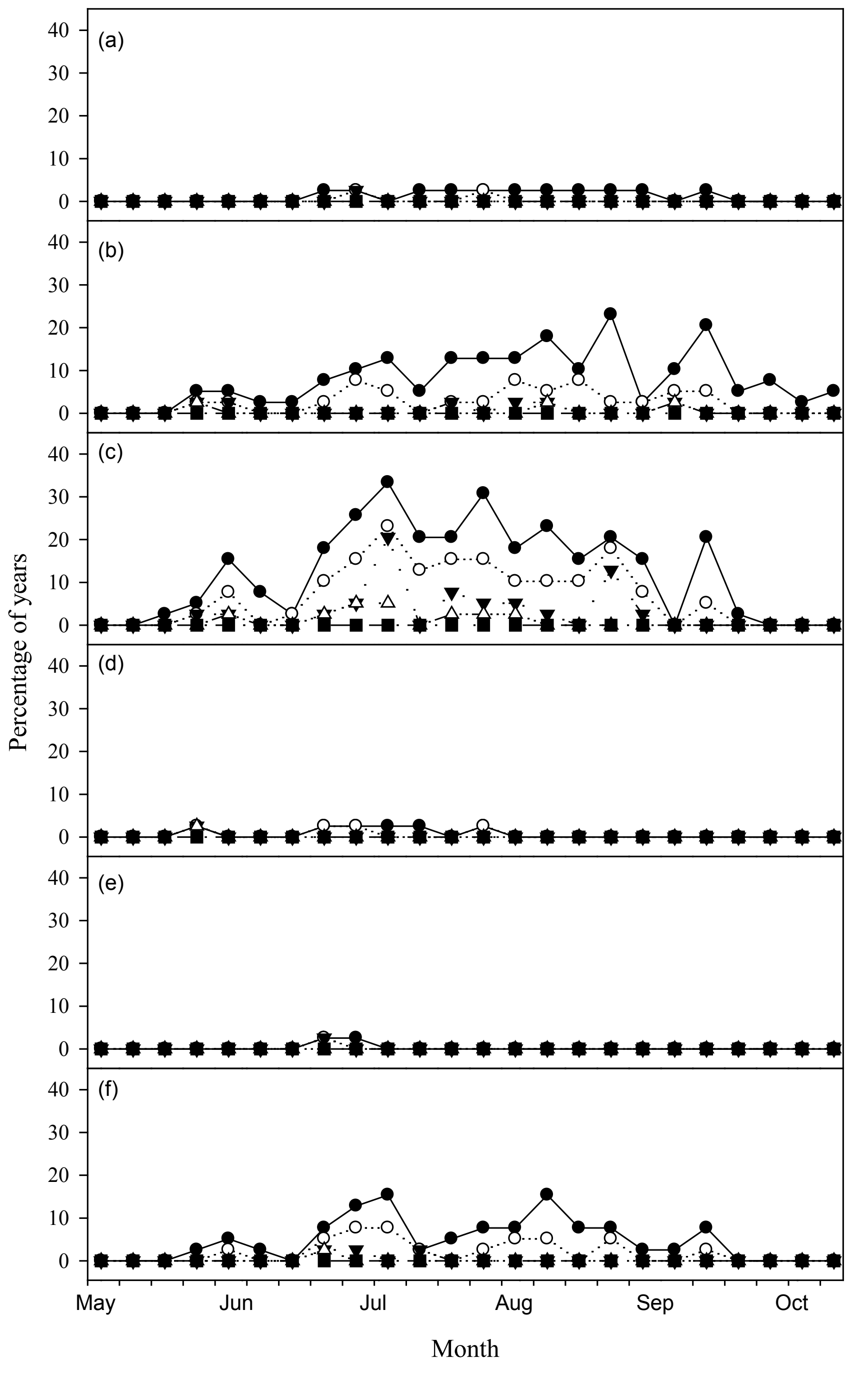

Figure 3: Likelihood of median weekly chill index exceeding 1100 kJ/m^2.hr for 24 weekly periods from May to October with 0 (–●–), 25 (○), 50 (--▼--), 75 (-Δ-··) and 100 (–■–) % wind speed reduction at Armidale (a), Hamilton (b), Orange (c), Tarcutta (d), Temora (e) and Yass (f).

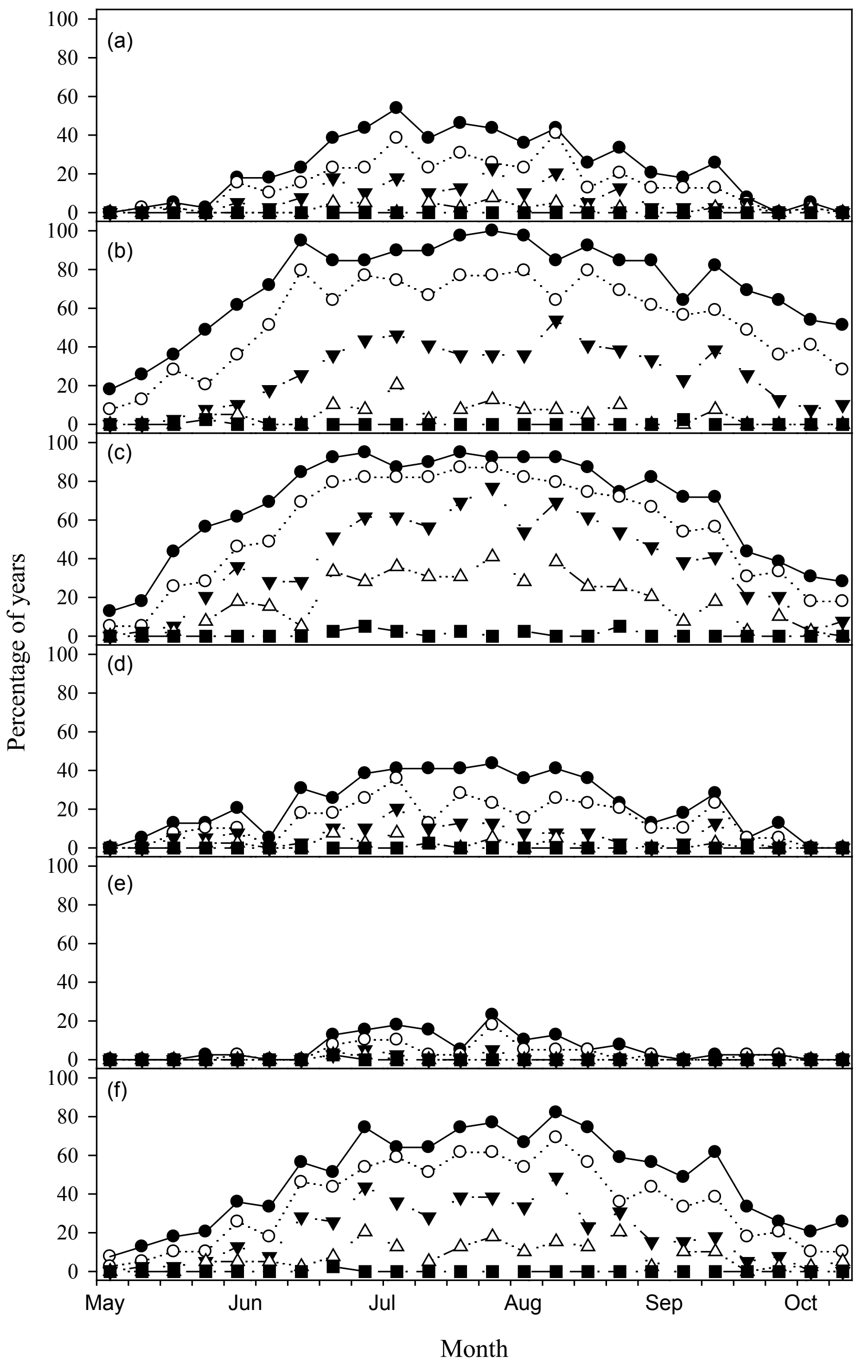

Figure 4: Likelihood of median weekly chill index exceeding 1000 kJ/m^2.hr for 24 weekly periods from May to October with 0 (—●—), 25 (○), 50 (--▼--), 75 (-Δ-··) and 100 (–■–) % wind speed reduction at Armidale (a), Hamilton (b), Orange (c), Tarcutta (d), Temora (e) and Yass (f).

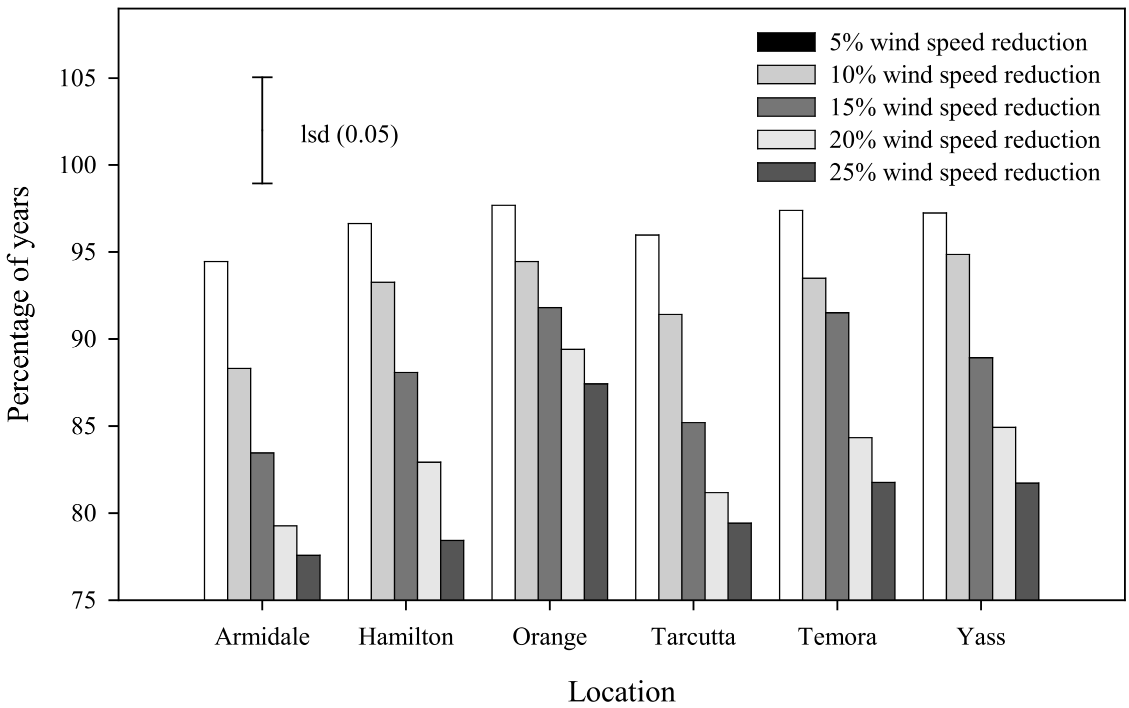

Figure 5: Percentage of years that the maximum chill index for a week exceeded 1100 kJ/m^2.hr over all 24 periods with reductions in wind speed compared to full wind speed (P<0.001, l.s.d. = 6.469).