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Shelter and shade for grazing sheep: implications for animal welfare and production and for landscape health

David G. Masters[A,B,*], Dominique Blache[A], Amy L. Lockwood[C], Shane K. Maloney[D], Hayley C. Norman[B], Gordon Refshauge[E] and Serina N. Hancock[C]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
David G. Masters
School of Agriculture and Environment, Faculty of Science, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
Email: david.masters@uwa.edu.au

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ABSTRACT

Shade and shelter may provide protection from cold and heat stress, a source of feed during prolonged or seasonal drought, specific essential nutrients, increased pasture and crop production and improved landscape health. Cold stress contributes to the average of 8% (single) and 24% (twin) of lambs that die within 3 days of birth in Australia and the estimated 0.7% of the Australian flock that die post-shearing during extreme or unseasonal weather. Shelter has resulted in an average reduction in mortality of 17.5% for twin-born lambs and 7% for single-born lambs according to Australian studies and decreases the susceptibility of ewes to metabolic disease and possibly dystocia. Because many of the published studies are from research areas where cold stress is expected, they are not indicative of industry-wide responses, a research priority is to determine the probability of lamb and ewe deaths from cold stress across different sheep production areas. Although shelter may improve lamb survival, ewes do not always choose to lamb in a sheltered location. For this reason, there is a requirement for research into the voluntary use of shelter in commercial-sized paddocks and the role that nutritive value of shelter plays in attracting and holding ewes to shelter, and to their lambs. Heat stress may also result in lamb deaths and influences feed conversion efficiency, appetite, reproduction, wool growth and disease susceptibility. The consequences of heat stress may go unnoticed over a yearly production cycle, although there is some evidence that shade may increase weaning rates and feed intake of grazing sheep. There are ancillary benefits from shade and shelter. Trees may improve crop production through reducing wind damage and evapotranspiration and provide timber. Shrubs provide feed during the summer–autumn feed gap or drought, are useful for the management of land degradation and provide habitat for native fauna. It is clear that shade and shelter in the correct locations provide a range of benefits to livestock and the landscape; nevertheless, adoption appears low. Research that focuses on defining the benefits on a farm or landscape scale is required to support extension programs.

Keywords: chill index, cold stress, drought feeding, heat stress, hypothermia, lamb survival, nutrition, shrubs.

Introduction

Shelter for grazing sheep provides protection from cold, wet and windy conditions or shade from excessive summer heat. The Australian Animal Welfare Standards and Guidelines for Sheep state the guideline 'that sheep and lambs should be provided with adequate shelter. In the absence of natural protection, consideration should be given to the provision of shade, windbreaks or sheds' (p. 11) (Animal Health Australia (AHA) 2016). Most shelter research has focused on reducing cold stress on lambs and lambing ewes. This is justified as an average of 8% (single) and 24% (twin) of all lambs born in Australia die within 3 days of birth (80% of total lamb deaths; Hinch and Brien 2014). High lamb mortalities have been reported in the UK (10–25%) and New Zealand (Mellor and Stafford 2004; Celi and Bush 2010), also with a high proportion of deaths in the first 48 h (Dwyer 2008). Similar mortalities would be expected in all cool or temperate climates where sheep are raised extensively. The extent to which hypothermia is responsible for these lamb deaths is uncertain as it may be part of a complex where starvation, birth injury and low birth weight increase susceptibility to cold. Cold stress during lambing may also contribute to ewe deaths either directly or through interactions with dystocia. There are few reliable data on the deaths of ewes during lambing although one study indicates ewe mortality of 2.5–3%, with 29–41% of these attributable to dystocia (McQuillan *et al.* 2021).

There have been many media articles, anecdotal reports and a few historical scientific studies (Geytenbeek 1962; Hutchinson 1968; Buckman 1982) on sheep deaths during unseasonal storms. Sometimes, but not always, these are associated with very low temperatures. Under such circumstances, significant benefits of shelter may be expected. A survey of sheep losses following the passage of a rain bearing depression during summer in south-Western Australia indicated that 27% of recently shorn sheep died during or shortly after the rain. Most sheep died from hypothermia, even though air temperatures were not low (13.3–21.7°C); conversely, sheep housed in sheds during the storm had close to zero mortality (Buckman 1982).

Heat stress may influence survival and production of both ewes and lambs. The consequences are probably underestimated, with few reports on the production responses from providing shade under commercial conditions. Arnold and Morgan (1975) reported 26–29% mortality from heat stroke in lambs born in summer. This may be a problem for the very few sheep farms in Australia that lamb during hot months (Croker *et al.* 2009), but is unlikely to be a serious industry problem as few farms in the major sheep production regions in Australia lamb during high temperatures (Hacker 2010). More importantly, under controlled conditions, heat stress has been shown to influence feed conversion efficiency, appetite, reproduction, wool growth and susceptibility to disease (Thwaites 1967, 1971; Sawyer 1979; Morrison 1983; Silanikove 2000; Marai *et al.* 2007; Phillips 2016; Moslemipur and Golzar-Adabi 2017). Under grazing conditions, similar changes may go unnoticed over a yearly production cycle.

Given the impact of heat and cold stress on lambing ewes and newborn lambs in winter and summer and on adult sheep during unseasonal rain and wind, benefits of shade and shelter would be expected. These benefits may have both economic and welfare implications. The use of shelter during lambing has been well researched and reviewed (Radcliffe 1983; Gregory 1995; Hawke and Dodd 2003; Pollard 2006), but there has been less research into the commercial production benefits of shelter and shade outside the lambing period, including the benefits on quantity and quality of the feedbase and on landscape health. The purpose of this review is to summarise research that has been conducted, identify potential production and welfare benefits that have not been evaluated, provide some preliminary guidelines on the use of shelter and shade and, present priorities for future research and extension. The focus is on the Australian sheep industry, but relevant information from elsewhere is also presented.

Changes in production and reproduction resulting from the use of shelter and shade

Metabolic consequences of cold and heat stress

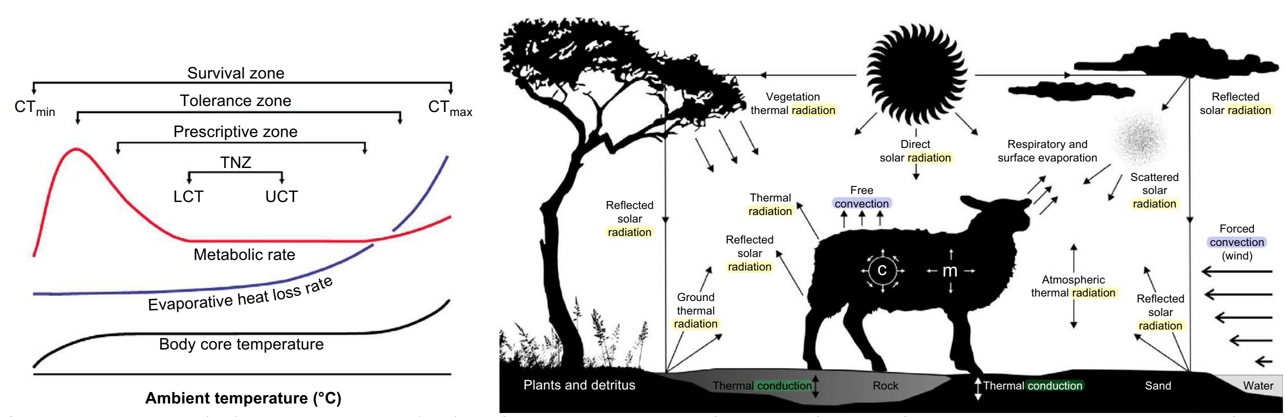
The metabolic response of a homeothermic animal, such as a sheep, to different environmental conditions can be expressed as a heat balance equation. In heat balance, heat inputs to the body are balanced by heat loss from the body. The generation of metabolic heat forms the central component of the equation, as follows:

$$\mathrm{MHP} \pm \mathrm{Cond} \pm \mathrm{Conv} \pm \mathrm{Rad} \pm \mathrm{Evap} \pm \mathrm{Work} \pm \mathrm{Storage} = 0$$

where MHP is metabolic heat production, and this term is always positive; Cond is heat exchange by conduction and depends on the temperature and thermal conductivity of anything that the body touches; Conv is heat exchange by convection and depends on the air temperature and wind speed; Rad is heat exchange by radiation and depends on the difference between emitted radiation, that depends on the fourth power of the surface temperature of the body, and received radiation, that depends on the fourth power of every surface that the body can 'see' and the emissivity (reflectivity) of the body to that received radiation; Evap is heat exchange by evaporation (or condensation), and in nearly all conditions this term is negative and can be modified by panting and sweating; Work is work against the environment, and for a sheep that is not moving, the term = 0; and Storage is heat storage in the body; any imbalance in the sum of the other terms results in either gain of heat to, or loss of heat from, the body. The change in body temperature then is a function of the heat capacity of the body, on average 3.5 J/g.°C.

Heat exchange by the routes above (summarised in Fig. 1) depends on the surface temperature of the body, which in turn depends on blood flow to the periphery. Metabolic heat is generated mainly in internal organs of the body and the heat produced by those organs is carried away from the organs and to the skin and respiratory tract by the blood. Thus, an increase in peripheral blood flow will result in an increase in skin temperature.

There is a range in environmental temperature, known as the thermoneutral zone (TNZ), within which a sheep can maintain body temperature by adjusting blood flow to the periphery, and without resort to extra metabolic heat production or evaporative heat loss (Fig. 1). The TNZ is framed by the lower critical temperature (LCT) at its lower end, and by the upper critical temperature (UCT) at its upper end. Below the LCT, a sheep will increase metabolic



Change in metabolic rate (red) evaporative heat loss (blue) and body temperature (black) as a function of ambient temperature (°C) in mammals. The thermoneutral zone (TNZ) is a smaller window than (1) the prescriptive zone, in which mammals are homeothermic and fully functional, (2) the tolerance zone, in which individual lives are not threatened but body temperature changes and physiological malfunction can occur (e.g. unable to reproduce) and, (3) the survival zone, in which individual lives are at risk (e.g. from heatstroke or cold injury). LCT is the lower critical temperature, UCT is the upper critical temperature, CT_{min} is critical thermal minimum, and CT_{max} is critical thermal maximum. Summit metabolism is at the peak of the red line. The different thermal zones are not necessarily centred.

Schematic representation of the routes of heat transfer between sheep and their environment. Sheep produce a significant amount of heat by metabolism (m) that is transferred throughout the body by convection in the blood and a small conduction component (c). Heat exchange by radiation (yellow highlight) is the largest single component of heat exchange, and exceeds conduction (green highlight) and convection (blue highlight). Radiant heat transfer is reduced under shade but is never zero since there are other sources of radiant heat, such as ground and vegetation. Air temperature and wind speed affect only the amount of heat transferred by convection. The amount of heat transferred by conduction is proportional to the area of contact between the sheep and the ground or any other object. In addition to behavioural responses that alter heat exchange by convection, conduction, and radiation heat, sheep, like other homeotherms, can dissipate heat by respiratory and surface evaporation. Evaporative cooling is a powerful mechanism if humidity is low in the environment and the sheep can spare the body water.

Fig. 1. Principles of thermoregulation in the sheep (adapted from both Porter and Gates (1969) and Mitchell *et al.* (2018)).

heat production to maintain heat balance, while above the UCT it will increase evaporative heat loss (see Fig. 1). The LCT is defined by a single environmental variable, air temperature, while heat balance is affected by many other factors. Thus, the LCT varies widely depending partly on animal factors (fleece length, feed intake, subcutaneous insulation, and posture) as well as environmental factors (wind speed, rainfall, and solar radiation). Anything that increases heat loss (removal of fleece, more wind, more rain) will increase the LCT. Gregory (1995) reported that the LCT for an adult sheep ranges from as high as 28°C when the sheep are shorn, wet, fed at maintenance and exposed to wind, to as low as −35°C when they have a full, dry fleece and are not exposed to wind. Similarly, Freer *et al.* (2007) reported that for 5 kg lambs, the LCT ranged from 28°C when the lambs had 8 mm wool, wind speed was 20 km/h and daily rainfall was 10 mm, to 18°C when the lambs had 14 mm of fleece and were under calm, dry conditions.

When the LCT is increased, more energy must be diverted from growth or production to the production of heat for maintenance of body temperature. That energy can be sourced from body stores or from increased feed intake. Using the equations of Freer *et al.* (2007), it can be estimated that the additional energy cost (above thermoneutral maintenance) to maintain body temperature of a wet 5 kg lamb with 8 mm of wool coverage at 5°C and 20 km/h of wind would be 3.0 MJ ME/day. This energy is additional to the maintenance requirement of the lamb and is equivalent to the energy required to support almost 200 g/day of growth in a thermoneutral environment (Agricultal Research Council 1980). The additional energy requirements would be lowered to 2.6 MJ ME/day if wind speed could be reduced by 10 km/h by using shelter (Fig. 2).

For an adult 50 kg shorn sheep approximately 7.3 MJ ME/day is required for maintenance under thermoneutral conditions (Freer *et al.* 1997). That requirement is increased by 13.9 MJ ME/day by exposure to 5°C,

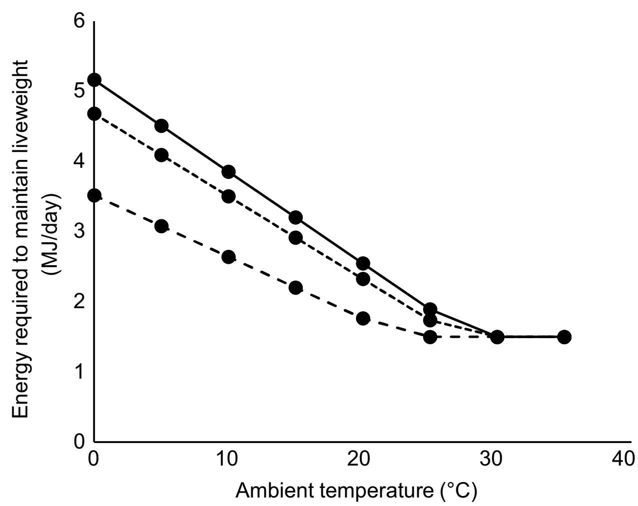


Fig. 2. Energy required to maintain liveweight of a 5 kg lamb with 8 mm wool cover in a wind of 20 km/h (solid line), 10 km/h (short, dashed line) or 0 km/h (long dashed line). All scenarios following 10 mm rainfall. Derived from equation 1.24 from Freer *et al.* (2007).

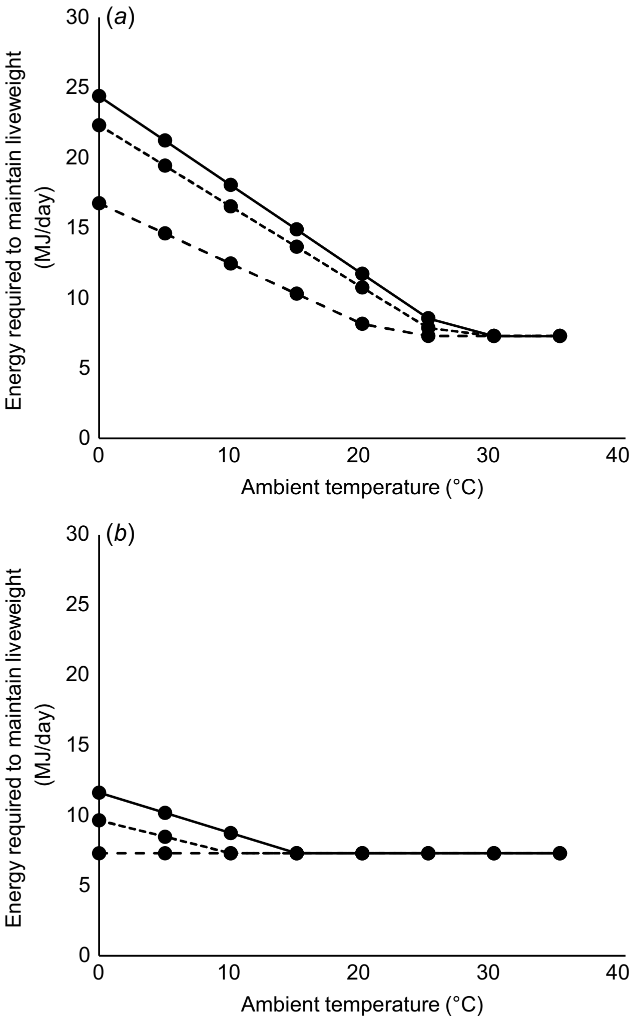


Fig. 3. Energy required to maintain liveweight of a 50 kg ewe with (*a*) 5 mm or (*b*) 50 mm wool cover in a wind of 20 km/h (solid line), 10 km/h (short, dashed line) or 0 km/h. All scenarios following 10 mm rainfall. Derived from equation 1.24 from Freer *et al.* (2007).

20 km/h of wind and 10 mm of rain (Fig. 3*a*). If wind speed is reduced to 10 km/h, the extra energy expenditure would be reduced to 12.1 MJ ME/day (Fig. 3*a*). Insulation with 50 mm of wool under similar weather conditions means that energy requirements increase by only 2.8 MJ ME/day (Fig. 3*b*).

For both lambs and shorn adults, the generation of enough heat through increased intake would be a challenge. Measured increases in feed intake of 46–78% in shorn sheep exposed to 7–10°C (Elvidge and Coop 1974) are consistent with the predictions of Freer *et al.* (2007). It is unlikely that shorn adults grazing short winter or dry summer pastures would be able to consume enough additional feed to meet the energy requirements of exposure to cold and rain. Subsequently, weight loss would be expected with a reduction in the efficiency of use of available nutrients for growth and production.

Even when sufficient energy is available from body stores or extra intake, there is another limit on the generation of heat. The maximum metabolic rate is known as summit metabolism, and under extreme cold stress the metabolic heat production that is required to achieve heat balance can exceed the summit metabolism (Fig. 1). Under those conditions, heat loss will exceed heat gain, hypothermia will develop, tissue oxygenation will decrease (hypoxia) and/or the partial pressure of oxygen in the blood will decrease (hypoxaemia) followed by death, regardless of feed availability or body stores. There are conflicting conclusions on whether summit metabolism increases following colostrum intake (Alexander 1962; Eales and Small 1980).

There is also an energy cost associated with heat stress, at least in sheep under controlled conditions. Those costs are given as 7% for rapid shallow panting (often called Phase I panting) and 11–25% for deep open-mouth panting (often called Phase II panting; National Research Council 1981). In a commercial production system, the total energy cost of heat stress is more difficult to quantify because temperature, other environmental parameters and animal behaviour that can mitigate stress all vary within the day.

Cold stress, shelter and lamb survival, health and production

In a study on Kangaroo Island between 1959 and 1963, the highest daily rate of lamb mortality was 54% for Corriedales and 91% for Merinos. These high rates occurred on days when wind speed was 24–56 km/h, rainfall ranged from 5.3 to 26 mm/day and average temperature ranged from 8.6°C to 12.3°C (Obst and Day 1968). Mortality was significantly higher when wind speed exceeded 8 km/h and daily rainfall exceeded 0.25–5 mm/day than on days when there was no wind or rain (Obst and Day 1968). Donnelly (1984) analysed data collected near Canberra between 1970 and 1971 and reported that the probability of death from exposure in the first 3 days of life for Merino lambs was up to 40% for singles and 60% for multiples. For crossbred lambs, the reported probabilities were 25% for singles and 40% for multiples. On low-chill days, the mortality of lambs born to ewes in good condition approached zero (Donnelly 1984). Across a range of environments, Dennis (1974) autopsied 4417 lambs from farms in Western Australia between 1963 and 1965 and reported exposure as the cause of death for 2.1% of lambs. More recently, Refshauge *et al.* (2016) autopsied lambs that died within 5 days of birth at sites across Australia between 2008 and 2011 and found that, on average, 5% of lambs died due to exposure. However, death varied among sites and years, with between 0% and 38% of lambs dying from hypothermia.

Low-birthweight lambs (often multiples) are at a higher risk of death than are heavy lambs (Refshauge *et al.* 2016). For survival, summit metabolism must meet or exceed heat loss. Summit metabolism is 71 kJ/kg.h for both single and twin lambs (Alexander 1962). However, heat loss is related to skin-surface area and summit metabolism per unit of surface area decreases as bodyweight decreases; this means larger, heavier lambs are better able to maintain body temperature than are small lambs, irrespective of birth status. When the cold-stress conditions on a lamb are below the tolerance zone (Fig. 1), summit metabolism is insufficient to balance heat loss, and hypothermia develops. A positive feedback cycle results because summit metabolism decreases as body temperature declines (Alexander 1962).

The benefits of shelter under such situations can be high; in a comprehensive 5-year study involving Merinos in New South Wales, where at least 40% of the lamb mortality was associated with hypothermia (Alexander *et al.* 1980), grass tussocks reduced the mortality in singles from 17% to 9% and in multiples from 51% to 36%. Wind protection alone saved many single lambs during poor weather but was less effective in protecting multiples unless the weather was fine. Low-birthweight multiples were more susceptible to hypothermia than were heavier lambs and prolonged poor weather resulted in hypothermia even in older lambs that had consumed milk. The observation that shelter improves survival has been confirmed in many other studies (McLaughlin *et al.* 1970; Egan *et al.* 1972, 1976; Robertson *et al.* 2011); these are summarised in Table 1.

The extent of the reduction in mortality is weather related, with many studies concluding that only twin lambs benefit from shelter. Twins are usually smaller than singles and more susceptible to high chill. Single-lamb mortality is often dismissed as non-significant (Egan *et al.* 1976; Robertson *et al.* 2011). However, while often not statistically significant, there is a consistent decline in death rates of single lambs (0–13%) as well as twin lambs (11–34%) at high-risk locations (Table 1).

In assessing the benefits of shelter, it is important to consider that many published results focus on locations, climates and events where lambing coincides with periods of high chill index. The chill index, which was derived by Nixon-Smith (1972) and modified by Donnelly (1984), is an indicator of potential heat loss and is calculated from temperature, wind velocity and rainfall. The studies undertaken in high-risk locations have well described the potential consequences but not the probability of those consequences. When weather conditions are mild and the chill index low, deaths due to cold stress are also low (Obst and Day 1968) and lamb survival is not improved by providing wind breaks (Lynch and Alexander 1976). Defining when shelter will be beneficial is not simple but can be partially addressed using the methodology of McCaskill and Clark (2007). They constructed wind roses to coincide with wind directions at times of bad weather during lambing and could quantify the percentage of time when the weather was bad enough to cause mortality. In a more comprehensive study (Broster *et al.* 2012*a*), the seasonal risk of cold stress was defined over 7-day periods for 24 weeks at six sheep growing locations in south eastern Australia. Weather conditions including wind, temperature, and rainfall were modelled using the GrassGro decision support tool (Donnelly *et al.* 1997). During the coldest months of the year, the median chill index exceeded 1000 kJ/m^2.h for nearly 100% of the time at some sites and less than 20% of the time at others. The threshold chill index of 1000 kJ/m^2.h was based on estimates of the summit metabolism in newborn lambs of 837–1255 kJ/m^2.h (Alexander 1962). A reduction in wind speed of 25% significantly reduced the median and maximum chill indices (Broster *et al.* 2012*a*). A key point from this study was that shelter will be far more effective in reducing chill index at windy locations and less effective where chill index is driven by temperature. A minimum starting point to encourage the broad establishment of shelter is to assess the risks at lambing time and across all sheep-growing regions by using methods similar to those of Broster *et al.* (2012*a*) or McCaskill and Clark (2007), and to use this information to estimate the expected number of lambs that could be saved, and calculate the financial benefit from the establishment of shelter at different locations.

Cold stress, shelter, ewe health, survival and production

Ewes, particularly those with a long fleece, have a very high cold tolerance (Fig. 3*b*). However, under extreme conditions, cold stress will compromise health and survival often through an interaction with body condition and metabolic disease. A combination of cold or emotional stress and short periods of starvation can induce pregnancy toxaemia, particularly if ewes are in poor condition (Reid 1962). Pregnancy toxaemia is a metabolic disease that can occur during late pregnancy when high energy requirements are not being met or when feed intake is depressed (Mavrogianni and Brozos 2008). The risk of energy imbalance is enhanced by an increase in energy requirements for the maintenance of body temperature and a possible reduction in digestive efficiency during cold stress (Young 1981). The resulting catabolic state causes high blood ketone concentrations and low blood glucose with increased ewe and fetal mortality. Early observations have described how adverse weather hastened the onset of 'undernutrition syndrome' due to a reduction in feed intake and an increase in energy requirement (Reid 1962). Paradoxically, the reduced intake and stress may be due to movement of the animals to a sheltered area without edible plants (Andrews 1997). The inappetence associated with pregnancy toxaemia can further result in hypocalcaemia and/or hypomagnesaemia. These metabolic diseases result from an acute shortage of available calcium or magnesium and can cause mortality of the ewe and fetus and, in a subclinical form, may be associated with uterine inertia and prolonged parturition (Friend *et al.* 2020).

Table 1. Influence of shelter on lamb mortality from experiments conducted in Australia between 1968 and 2011.

Lambing birth type	Breed	Lamb mortality (%)			Shelter type	Paddock size (ha, except when indicated otherwise)	Location	Reference
		Sheltered lambing	Exposed lambing	Shelter benefit				
Single	Merino	9	17	8	Grass hedge	0.4	Armidale, NSW	Alexander *et al.* (1980)
Single	Merino	6	19	13	Trees/shrubs	0.8–1.5	Hamilton, Vic.	Egan *et al.* (1972)
Single	Merino	10	12	3	Grass	0.1	Hamilton, Vic.	Egan *et al.* (1976)
Single	Corriedale	7	13	7	Trees/shrubs	1.5–2.5	Hamilton, Vic.	McLaughlin *et al.* (1970)
Single	Merino cross	22	25	0	Hedge/shrubs	1	Tarcutta, NSW	Robertson *et al.* (2011)
Single	Corriedale	8	21	13	Various	Pens	Western Vic.	Watson *et al.* (1968)
Single	Merino	5	11	6	Grass hedges	<0.4–0.8	Armidale, NSW	Lynch and Alexander (1977)
	Average			7				
Twin	Merino	13	27	15	Trees/shrubs	0.8–1.5	Hamilton, Vic.	Egan *et al.* (1972)
Twin	Merino	19	31	12	Grass	1.5–2.5	Hamilton, Vic.	Egan *et al.* (1976)
Twin	Corriedale	6	25	19	Trees/shrubs	1.5–2.5	Hamilton, Vic.	McLaughlin *et al.* (1970)
Twin	Merino	41	68	27	Grass hedges	0.4–0.8	Armidale, NSW	Lynch and Alexander (1977)
Twin	Merino cross			>4.0	Trees/shrubs	1.3	Tarcutta, NSW	Robertson *et al.* (2011)
Twin		24	58	34	Various	Pens	Western Vic.	Watson *et al.* (1968)
Twin	Merino	27	12	15	Oats, double row	1	Wooroloo, WA	Glover *et al.* (2008)
Twin	Merino	27	26	1	Oats, single row	1	Wooroloo, WA	Glover *et al.* (2008)
	Average			17.5				
Multiple	Merino	36	51	15	Grass hedges	0.4	Armidale, NSW	Alexander *et al.* (1980)
Singles + twins	Merino	21	39	17	Grass hedges + polythene mesh	12	Armidale, NSW	Lynch *et al.* (1980)

Cold stress can also directly influence survival. In Australia, historical data indicate that the mortality of ewes and lambs post-shearing is 0.7% of all sheep (Hutchinson 1968). Over 75% of these deaths are within 14 days of shearing (Hutchinson 1968). Individual flocks and regions can have a much higher death rate than the average. Geytenbeek (1962) reported mortality within 5 days of shearing of 13.9% for Merinos and 8.2% for Corriedales and Crossbreds from a survey of 17 properties in the Kybybolite region of South Australia. Overall mortality rates of 26–28% have been reported for recently shorn sheep in the south-western and central wheatbelt in Western Australia under poor weather conditions (Buckman 1982; Glass and Jacob 1992). Glass and Jacob (1992) observed mortality of 90% on one farm where sheep were shorn less than a week before adverse weather. Hence, the risk of mortality after shearing is exacerbated with heavy rain and a cold wind, particularly when sheep are in poor body condition (Geytenbeek 1962; Hutchinson 1966, 1968). Deaths may be reduced to zero with adequate shelter, although high mortalities have been recorded even when paddocks were considered well sheltered (Geytenbeek 1962; Buckman 1982; Glass and Jacob 1992).

This may be due to the positioning of shelter being ineffective against the prevailing winds, insufficient density of shelter at the level of the sheep, shelter being provided too late or extended periods of exposure to heavy rains (Glass and Jacob 1992).

It would be expected that the requirement for energy to be diverted for the maintenance of body temperature during cold stress would mean a depression in growth and production. In Welsh Mountain ewes under cold conditions and controlled feed intake, outdoor exposure led to a 1.5 kg reduction in bodyweight pre-partum, equivalent to a 10% reduction in daily digestible organic-matter intake. The growth rate of wool was unchanged (Robinson *et al.* 1973). Conversely, in Scottish Blackface sheep wool growth was reduced under cold conditions in climate-controlled chambers (Slee and Ryder 2009). The diversion of energy to thermoregulation affects other physiological systems. An artificially induced stress that included simulated rain in a cold environment reduced ovulation rate by 8–42% (Doney *et al.* 1973). Cold stress on the ewe will also influence the development and subsequent survival of the fetus. Lambs from recently shorn ewes or ewes in poor condition are more likely to die from hypothermia than lambs from unshorn, well fed ewes (Alexander *et al.* 1980; Donnelly 1984; Oldham *et al.* 2011), although shearing does not always increase the risk of mortality if shelter is available (Lynch and Alexander 1976). Shearing in mid-pregnancy may also result in increased birthweight, although results are inconsistent (Kenyon *et al.* 2003). There is a well documented relationship among ewe condition, lamb birthweight and lamb survival. Ewes in better condition tend to be more insulin-insensitive, resulting in the partitioning of more glucose to the fetus and in heavier lambs with higher fat reserves that are less likely to die around the time of birth (McNeill *et al.* 1997). Less well understood are the possible effects of thermal stress on gene expression in the ewe and fetus and the potential for epigenetic changes. These are apparent in cultured cells (Sonna *et al.* 2002), with some evidence of changes in living organisms (Abe *et al.* 2018).

There are few reports on the direct impact of shelter on cold-stressed, adult sheep under commercial conditions. In one study, there were fewer shepherding problems (dystocia or mismothering) in ewes with shelter (Pritchard *et al.* 2021); however the number of ewes in this unreplicated study was small. The lack of reports on changes in production are possibly due to an increase in feed intake and compensatory growth under extensive production. Nevertheless, because energy is used for heat production, cold stress would reduce the efficiency of feed use for production and therefore also reduce the sustainable stocking capacity, particularly when grazing early season, slow growing winter pastures.

Heat stress, shelter and ewe and lamb survival, health and production

Controlled environment

Much of the research into the consequences of heat stress on sheep has been under controlled conditions, often in a climate-controlled facility. With sustained heat stress (days rather than hours), feed intake, feed digestibility, liveweight and wool growth are reduced, water intake increased (Thwaites 1967; Marai *et al.* 2007), and early embryo death and returns to service are both increased (Dutt *et al.* 1959; Smith *et al.* 1966; Thwaites 1971). Heat stress disrupts the oestrus cycle, slows placental growth, depresses lamb number, and results in low-birthweight lambs (Sawyer 1979; McCrabb *et al.* 1993; van Wettere *et al.* 2021). Exposure to high temperatures even for short periods prior to mating (32°C on the 12th day of the cycle before breeding) significantly reduces ova fertilisation (Dutt *et al.* 1959; Dutt 1964). In males heat stress is associated with fewer sperm per ejaculate, abnormal sperm and reduced sperm motility (Smith 1971). Short-term heat stress is associated with elevated oxidative stress, increased cortisol and catecholamines and reduced thyroid hormones in plasma (Silanikove 2000; Lowe *et al.* 2002; van Wettere *et al.* 2021) Blood flow changes (Hales 1973), and panting increases the risk of alkalosis (Barnes *et al.* 2004). These changes are associated with altered neurological function with the lowered partial pressure of carbon dioxide in the cerebral blood vessels causing vasoconstriction and reduced perfusion of the brain (Stockman *et al.* 2011). High humidity exacerbates the heat stress that is caused by high ambient temperature because evaporation is not as effective when humidity is high.

Grazing sheep

In sheep flocks grazing in tropical and arid conditions, high temperatures cause lower lamb birth weight and often the death of newborn lambs (Arnold and Morgan 1975; Hopkins *et al.* 1980). The availability of shade can significantly increase the weaning percentage (Stephenson *et al.* 1984). Under extensive grazing in temperate or Mediterranean environments, variation in temperature and humidity across and within days, combined with behavioural thermoregulation, can reduce the likelihood of the sustained heat stress that is observed under controlled or tropical conditions (Brown 1971); nevertheless, reduced embryo survival and fertility, along with increased returns to service, have been associated with high temperatures during or just after mating (Kleemann and Walker 2005). Even short periods of heat stress in grazing ewes can depress appetite and compromise placental growth (McCrabb and Bortolussi 1996). In the field, this heat stress can interact with other environmental and nutritional factors to exacerbate the issue; for example, digestion of the low-quality pastures that are often associated with high environmental temperatures will generate more heat per unit of metabolisable energy (ME) and therefore contribute more to the overall heat load on the animal (Webster *et al.* 1975). Increased walking for water and feed will increase energy use and heat production. Panting can disrupt the acid–base balance and increase the requirements for mono-valent ions such as sodium, potassium, and chlorine (Silanikove 2000; Barnes *et al.* 2004). In sheep exposed to heat in an indoor facility, the oxidative stress that is associated with heat can be partially alleviated by feeding supranutritional amounts of antioxidants such as vitamin E (Chauhan *et al.* 2014*a*, 2014*b*).

The consequences of heat stress in grazing sheep may not therefore be immediately apparent but will affect long-term growth and reproduction. There is sufficient evidence to indicate that the reduction of heat stress should be a priority, particularly during mating and pregnancy.

Because radiation is a major avenue of heat gain on cloud-free days (Fig. 1), benefits of shade to sheep under heat stress would be expected; but benefits have not been conclusively demonstrated. Johnson and colleagues (Johnson 1987, 1991; Sherwin and Johnson 1990; Johnson and Strack 1992) investigated the provision of shade in sheep at maximum ambient temperatures up to 50°C and observed few differences in feeding, drinking or ruminating between sheep that chose to use shade and those that had shade available but chose not to use it. Silanikove (1987) reported that shade reduced the respiration rate and body temperature but had no effect on bodyweight or feed intake. In a later publication, Silanikove (2000) concluded that the incidence of heat stress is highly dependent on shade, feed amount and composition and water availability and quality. Much of the support for the benefit of shade has been based on responses in cattle rather than sheep.

Changes in behaviour resulting from the use of shelter and shade

Cold

How the ewe and lamb choose to interact with shelter and with each other is critical for achieving the benefits that are available. To gain protection from wind and possibly rain, the ewe will need to voluntarily seek shelter during poor weather and during lambing. Most studies on shelter and behaviour during lambing have been in small paddocks, plots, or even sheds (Table 1). There have been few studies on behaviour and voluntary use of shelter at the commercial scale. In small plots, grass rows as far apart as 240 m were used by recently shorn, lambing ewes, but less so by unshorn sheep. Shearing ewes 4–9 days prior to expected lambing increased the use of shelter during both nights and days, either before or after lambing (Alexander *et al.* 1979). Shelter was used more at night and during bad weather by shorn (but not unshorn) ewes (Mottershead *et al.* 1982). Grass shelter was preferred to black plastic mesh, but many ewes preferred to lamb in isolation, away from shelter (Alexander *et al.* 1979). In contrast, Broster *et al.* (2017) observed that a higher than expected number of ewes lambed close to shelter rows and in New Zealand experiments a high proportion of lambs used shelter on commercial farms (Pollard and Littlejohn 1999). Stevens *et al.* (1981) reported that Merino ewes in moderate-sized paddocks did not seek isolation at lambing and tended to lamb where the flock was grazing or resting at the commencement of parturition. A high proportion of ewes lambed in shelter because this was where the flock was located at the time. Others have reported frequent use of shelter in ewes in moderate-sized paddocks (Lynch *et al.* 1980; Taylor *et al.* 2011). The inconsistent conclusions warrant further investigation to determine whether sheep will seek shelter in large paddocks or whether shelter can be made more attractive, or whether small, specialised lambing paddocks are required.

During the postnatal period, ewe appetite will increase. This too may influence behaviour. Studies on interactions between food preference and social bonds have indicated that ewes will try to maximise energy gain (Dumont *et al.* 1998), and forage availability and quality will influence the distance that ewes will travel away from social groups (Dumont and Boissy 2000). Energy may not be the only nutritional attraction. During late pregnancy and parturition, ewes are susceptible to metabolic disturbances related to calcium, magnesium, sodium and potassium availability such as hypocalcaemia and hypomagnesaemia. The transition period (3 weeks before to several weeks after parturition) is a time of high oxidative stress, with a potential increase in the requirement for antioxidant nutrients (Masters 2018). Such nutrients are often found in high concentrations in some of the shrubs that are used for shade and shelter (Norman *et al.* 2019). Therefore, in making shelter more attractive, investigations should include the nutritional value of the shelter material and whether the provision of energy, protein or specific nutrients in addition to protection from the wind chill will increase the use of a shelter. Familiarity, through nutritional value and novelty, should be considered as a means of attraction. The ewe faces behavioural decisions on whether to remain with the lamb or to leave to seek a nutritional benefit.

The successful adoption of shelter by ewes at lambing will reduce cold stress but may not be sufficient on its own to take full advantage of potential benefits. For this, the shelter will also need to increase the time that ewes spend at the birth site and encourage interaction between the lamb and ewe. The survival of lambs, particularly multiples, depends on the establishment of a strong ewe–lamb bond which decreases the incidence of separation (Nowak 1996). The development of a strong bond between ewe and lamb is considerably improved if the mother remains on the birth site for a minimum of 6 h after birth (Nowak and Poindron 2006). Merino ewes tend to spend only a short time near the birth site and, consequently, up to 40–50% of twin lambs can become separated from their mother. Lambs are a partner in this process and in early life (12–24 h) can identify their mother only at close range (0.05 m) (Nowak 1996). When considering shelter, the visual distance between lamb and ewe may be more important than the linear distance (Knight *et al.* 1989), meaning that short or porous shelter would be preferable to high, dense shelter. In line with this suggestion, ewes travelled less in the 24 h after birth when shelter was provided as porous shrubs than when it was 1 m high hessian (Broster *et al.* 2017) and there was 17% less contact between ewes and twin lambs with hessian shelter than with shrub shelter (Broster *et al.* 2010).

Heat

Some studies on the behaviour of sheep offered shade have provided evidence that voluntary shading is not a priority, even at maximum ambient temperatures up to 50°C (Johnson 1987, 1991; Sherwin and Johnson 1990; Johnson and Strack 1992). Conversely, Stafford Smith *et al.* (1985) demonstrated that a respiration index is correlated with shade-seeking behaviour and that this behaviour is further modified by the need for feed and water. The results of Stafford Smith *et al.* (1985) are more consistent with the common site of flocks of sheep resting in the shade of large trees on hot days. To our knowledge, the impact of fleece length on shade-seeking behaviour has not been investigated. It is likely that fleece length would influence the use of shade because it affects radiation heat load and the capacity of sheep to dissipate surface heat. Wool length up to 4 cm provides insulation and reduces radiant heat load (Al-Dawood 2017). However, Merino sheep with a long fleece length (>8 cm) were less able to regulate body temperatures than recently shorn sheep when facing hot but humid conditions (33°C dry bulb temperature; 55% relative humidity; Beatty *et al.* 2008).

Technology to monitor animal behaviour, health, and welfare and the physical environment

Weather stations have been used for many years to collect data that are used to characterise the grazing environment. Such information, sourced from regional meteorological stations, is the basis to the chill index used to alert graziers to the risk of death in lambs and shorn sheep (Nixon-Smith 1972; Donnelly 1984). Technological advancement has meant miniaturisation and reduced unit costs to allow microclimate comparisons within and between sheltered and unsheltered paddocks (Robertson *et al.* 2011; Broster *et al.* 2017). For a useful assessment of shelter, information is also required on the interaction between animals and shelter. Much of the published research on this interaction has been the result of meticulous manual observation and recording (Alexander *et al.* 1979; Pritchard *et al.* 2021). While this is of great value, it is limited by the need for labour, is restricted to daytime application and observation may influence behaviour. More recently, GPS collars have been used compare the movements of ewes and lambs (Taylor *et al.* 2011; Dobos *et al.* 2015; Broster *et al.* 2017) and contact loggers have been used to compare interactions between ewes and lambs across different types of shelter (Broster *et al.* 2010, 2012*b*). Now there is information not just on mortality with different weather conditions, but an understanding of the changes in behaviour of the ewes and lambs in response to shelter options. More is possible; for example, accelerometers can provide information on grazing behaviour as well as walking and resting (Giovanetti *et al.* 2017) and intraruminal temperature loggers have been used to monitor drinking events (Vazquez-Diosdado *et al.* 2019).

Technology is now also available to directly monitor the health and welfare of ewes and lambs under experimental conditions using implanted or indwelling devices, such as probes under the skin that extend deep into animal tissues and devices that lodge in the digestive tract. Some of the devices weigh a few grams and have a battery life of 5–10 years (Maloney *et al.* 2019; Lewis Baida *et al.* 2021). Tympanic temperature sensors are being used in cattle to detect fever related to illness (Lewis Baida *et al.* 2021). The deep-core temperature is the gold standard to assess heat stress in homeotherms (Maloney *et al.* 2019). Measurement of skin-surface temperature, subcutaneous temperature or tympanic temperature must be considered carefully because they can be affected by local convection and conduction. Nevertheless, the relationship between the measured internal and external environments, and the interactions of the animal with the physical environment may provide a further indicator of stress and welfare.

Shade, shelter and nutrition

Edible and non-edible shelter

The most common forms of tested shelter are trees, shrubs, grass, vegetative crops, and hessian barriers (Bird *et al.* 1992; Glover *et al.* 2008; Broster *et al.* 2010, 2017). Trees (particularly when mature), rocks and gullies and hessian provide little or no edible dry matter; all other options are edible. Vegetative crops and forages are edible and very palatable, shrubs are usually edible while nutritional value and relative palatability are variable, and mature grass hedges or tussocks are edible but, when mature, have poor nutritional value and are unpalatable. In addition, vegetative crops and forages tend to be uniformly spread over the paddock while shrubs tend to be planted in block or hedgerows. These differences provide opportunities for innovative shelter design; for example, shrubs such as *Atriplex* spp. may provide shelter and are eaten by grazing sheep, other shrubs such as *Rhagodia preissii* provide shelter but are not a preferred diet option (Revell *et al.* 2013), a shelter with a combination of these shrubs may be attractive to sheep as a food source but also will remain as a functional shelter because of the unpalatable *R. preissii*.

Nutrients from edible shelter

Plants that provide shelter, shade and a feed supply may be more attractive to animals than are shelter and shade with no nutritional value. They may improve the nutrition of the sheep and, at lambing, encourage the ewe to stay in the vicinity of the lamb. While this seems a logical hypothesis, it is not one that has been tested. Of the edible plants, shrubs and trees will provide both shade and shelter while grass hedges and vegetative crops will have some value as shelter but are either too short to provide shade or do not grow during hot seasons of the year. Many herbaceous plants elongate and become taller as they move from vegetative to reproductive phases, this means that shelter value is increasing as nutritional value declines (Norman *et al.* 2021).

Shrubs and trees

Shrubs that are suitable for shelter vary in edible biomass production, nutritive value and palatability. Lefroy *et al.* (1992) reviewed forage trees and shrubs in Australia and concluded that the cultivated species most likely to provide nutrient for livestock include tagasaste (*Chamaecytisus palmensis*) and the tropical species *Leucaena leucocephala*. Robertson and colleagues (Robertson *et al.* 2011; Broster *et al.* 2017) used *Acacia* spp. in a series of studies. *Acacia* spp. usually have a very low digestibility (organic-matter digestibility 27–57%, usually <50%) (Norman *et al.* 2010*a*; Revell *et al.* 2013) and are unlikely to provide enough ME to contribute significantly to growth and milk production. There are many other shrub options, some with digestibilities high enough to support a moderate level of production and crude protein (CP) well above the requirements for reproducing sheep (Wilson 1977; Lefroy *et al.* 1992; Revell *et al.* 2013). The amount of biomass produced by most shrubs is small compared with pasture production and they will provide a supplement across a range of environments rather than a standalone feed source (Lefroy *et al.* 1992; Ben Salem *et al.* 2010). The value as a supplement may be significant, because these shrubs contain macronutrients, essential micronutrients and secondary compounds that may have both nutritional benefits and nutraceutical properties. Many contain high concentrations of vitamin E and other antioxidants (Pearce *et al.* 2005; Fancote *et al.* 2013; Norman *et al.* 2019), others have been shown to contain compounds that have anthelmintic properties and reduce methane production during rumen fermentation (Kotze *et al.* 2009; Vercoe *et al.* 2009). Mineral composition is also quite different from that of traditional pasture plants (Revell *et al.* 2013). Providing this diversity of nutritional and paranutritional options within a grazing system has been advocated by Provenza and Villalba (2010) as a strategy to enhance health, intake and preference and by Altieri *et al.* (2015) to provide a more resilient landscape. Evidence that the plants are attractive and provide a novelty factor has been demonstrated, with sheep choosing to make shrubs part of their diet even when there is unlimited high-quality pasture available (Norman *et al.* 2010*b*).

Trees in Australia do not usually provide a useful supply of nutrients to grazing ruminants. There is often edible biomass, for example, from fallen leaves, fruit, or edible pods but these are usually low in quantity and digestibility. Experiments with grazing sheep in agroforestry systems under *Pinus radiata* have indicated that pine needles have a very low digestibility (~36%) and that fallen pine needles will decrease the quality of pastures growing under the trees (Hawke *et al.* 1993). Conversely, in arid regions of the eastern Mediterranean and Asia, mulberry leaves (*Morus* spp.) are considered a high-value supplement for ruminants (Sánchez 2002).

Herbaceous pasture plants

Grasses and other herbaceous forage plants must be left ungrazed until they are high and dense enough to provide a windbreak at lambing. This may be for most of the growing season and, under drought conditions, there may be insufficient growth to offer shelter. For grasses, this means the tussocks that provide the best shelter value are likely to be rank, have low ME and CP and be high in fibre. For example, tall wheat grass (*Thinopyrum ponticum*) at flowering has a dry-matter digestibility (DMD) of ~46% and CP of 3.4–3.6% (Smith *et al.* 1994). This is well below the requirements for the liveweight maintenance of a non-pregnant adult ewe of approximately 60% DMD and 11% CP (Freer *et al.* 1997). If the plants are managed to prevent flowering, DMD may be 60–85% with CP 15–30%. Other perennial grasses have similar nutritive value; for example, *Phalaris aquatica* (Toowoomba canary grass) and *Lolium perenne* (perennial ryegrass) harvested after anthesis have DMD below 40% (Lam *et al.* 2003). *Bituminaria bituminosa* (tedera) is an untested option; it is an erect plant with a DMD >60% and CP >12% (Oldham *et al.* 2015).

Herbaceous legumes generally offer greater feeding value than do grasses. Norman *et al.* (2021) compared changes in growth and nutritional value during the lifecycle of many of the perennial legume species that are suited to southern Australia. Of the 20 species examined, there was significant variation in biomass production and nutritional value in later stages of plant maturity. Perennial clover species (*Trifolium repens*, *T. pratense* and *T. hybridium*) had the highest nutritional value during senescence (61–66% DMD and 13–14% CP). These clover species struggle to persist in rain-fed mixed farming systems, may lodge when left ungrazed, and may not be sufficiently tall to provide shelter. Sulla (*Hedysarum coronarium*), lucerne (*Medicago sativa*) and sainfoin (*Onobrichis vicifolia*) persist in dry environments and have upright growth habits. Mature, ungrazed stands offer

DMD of 57–61% and CP of 12–16%. Sulla is interesting as it regrows rapidly from the crown in autumn and reaches a significant height before growth is impeded by cold temperatures in winter. If high feeding value results in patchy shelter, there are commercialised herbaceous perennial legumes with very poor feeding value. For example, hairy canary clover (*Dorycnium hirsutum*) produces biomass with very low nutritional value, even in the vegetative phase (DMD < 50%, CP 16%; Norman *et al.* 2021). Although not commercialised, there are several native perennial legumes that may also offer an opportunity as an 'edible' shelter, including cullen (*Cullen australasicum*), *Indigofera australis* subsp. *hesperia* and *Glycyrrhiza acanthocarpa* (Bennett *et al.* 2011; Snowball *et al.* 2021).

Vegetative crops

Young crops provide a good supply of highly digestible forage (>80% DMD) with high ME (>12 MJ/kg DM) and CP (>20%) in the early part of the growing season, often when pasture supply is limited (Masters and Thompson 2016). As crops age, their nutritive value declines but still remains adequate for growth and production (de Ruiter *et al.* 2002). The ME and CP content of the crops exceed the minimum requirements for pregnancy and lactation; however, the mineral composition of some crops is imbalanced. A significant proportion of wheat, oat and barley vegetative samples contain less calcium, magnesium and sodium than is required by pregnant sheep and the mineral ratios are consistent with a risk of metabolic disturbances (such as hypocalcaemia and hypomagnesaemia; Dove *et al.* 2016). There is very little known about the impact of grazing cereal crops during lambing on ewe and lamb survival. If animals are removed from crops prior to stem elongation, the yield of harvested grain is usually maintained (Harrison *et al.* 2011). If the crops are grazed by ewes lambing in autumn of winter, there may be insufficient height to provide shelter; alternatively, if grazed by late winter- or spring-lambing ewes, when crops are high enough to provide shelter, a loss of yield may result. Thus, under conditions where cold stress compromises lamb survival, there may be a trade-off between lamb survival and loss of yield at harvest.

Shelter options for grazing sheep

Shelter prevalence

There are very few data on the amount or adequacy of the shelter that currently exists on sheep farms in Australia and New Zealand. Earlier studies from New Zealand, where cold, wet, and windy weather in sheep regions is common, have indicated that in mid-Canterbury only 1% of land was occupied by shelter (Sturrock 1973) and fewer than 23% of farms had one or more shelter belts (Scales 1994). This information is well out of date due to changes in farming systems in the region. More recently, the majority of sheep farmers who were surveyed identified shelter as important and indicated they were likely to plant shelter in the future (Fisher 2010). The lack of more information is consistent with a low priority for formalised, constructed or planted shelter or shade.

Shelter design and function

Shelter and shade can provide protection from wind, rain, snow and sun and influence both plant and animal health and production. Farmers aiming to provide shelter for livestock also need to consider the consequences for other enterprises and production rotations (e.g. cropping). The enterprise mix will influence the choice of appropriate design and location; there is no single best option.

Selection

Shelter may be planted, built or natural. Natural shelter includes humps, gullies, logs, rocks or natural vegetation. Planted shelter must be appropriate for the soil and environmental conditions and, in most circumstances, indigenous or locally adapted species should be considered first. As the establishment and maintenance of shelter can be expensive, the most economical path will be through the retention and management of natural trees and shrubs (Ritchie 1988). The most common plants and materials used and tested include trees, shrubs, perennial grass tussocks, hessian barriers (or other material such as iron, timber or hay bales), and, to a lesser extent, vegetative crops. Each option has advantages and disadvantages (Table 2). Biological options must have enough vegetative growth to be effective when required (usually during lambing or heat wave conditions). The shelter must be considered within the context of the whole farming system.

Trees have been used in a number of configurations including a single line, a woodlot or block of trees, forest grazing or agroforestry where trees and pasture are grown together for forestry and grazing (Gregory 1995). Shelter and shade from trees may be preferred where timber is potentially a co-product on the farm (Sturrock 1988). Animals may either be excluded or graze within the trees. Trees reduce wind speed by up to 80% close to the row, and continue to provide a significant windbreak at a distance of 5–10 times the height of the trees (Dronen 1988; Bird *et al.* 1992). Trees are a long-term commitment; however, additional benefits may be gained through oil production, biofuels or carbon credits.

Shrubs offer a shelter and shade option; rows of mixed *Acacia* spp. reduced the maximum wind speed in lambing paddocks by 12–53% at a distance 2.5–10 times the height of the rows (Broster *et al.* 2017). Hedgerows of cypress (*Cupressus macrocarpa*; 5–10 m high) reduced average wind speed by 60–70% within 20 m of the hedge

Table 2. Advantages and disadvantages of different shelter option.

Shelter option	Advantages	Disadvantages
Trees	• Protects large area adjacent to the trees • Shelters crops, forage and soils from wind damage and reduces evapotranspiration • Landscape benefits through reduced wind and water erosion and water-table drawdown for salinity management • Provides shade, shelter and habitat to insects, fauna and livestock • Timber and oil production • Carbon-farming opportunity	• Low edible dry matter and green leaves above stock grazing height • Poor nutritive value • Reduced crop and pasture growth adjacent to the tree • Long-term commitment of land (reduced flexibility) • Difficult to locate in cropping landscapes where seeding and harvesting equipment are wide and operated using guidance • Cost and time lags during establishment
Shrubs	• Edible dry matter of low to medium nutritive value but with a high content of some nutrients (e.g. antioxidants and minerals) • Provides both shade and shelter • Correct design will allow visibility between ewe and lamb • Palatable and unpalatable shrub mix to manage vegetation • Landscape benefits through reduced wind and water erosion and water-table drawdown for salinity management • Provides shade, shelter and habitat to insects, fauna and livestock • Low opportunity cost with shrubs that grow on saline, sandy or uncroppable soils • Feed and shelter during seasonal and long-term drought	• Nutritional constraints (e.g. high salt) and secondary compounds (oxalate, saponins and tannins) • Mostly local protection with some benefits to adjacent land • Medium-term commitment of land (reduced flexibility) • High up-front cost of establishment if nursery-raised seedlings are used • Time lags during establishment • Increased management complexity as small-scale equipment may be needed for management of the understorey
Grass (tussocks)	• Good protection from wind adjacent to tussocks • Some edible dry matter • Usually allow visibility between ewe and lamb (may require management) • Easy to remove or relocate	• Tussocks often rank with poor nutritive value • Paddock to be vacated before use to allow tussocks to grow. Results in an economic loss from delayed grazing • Most likely option is to set up as a small, designated lambing paddock • Will offer shelter from wind but no shade • No growth during drought
Vegetative crops and forages	• Very flexible, relatively inexpensive to establish and fits within a mixed farming system • Grain or forage harvest following grazing • High edible dry matter • High nutritive value • May allow visibility between ewe and lamb	• Limited research validation • Loss of harvestable crop yield (plant genotype, growth stage and grazing intensity-dependent) • Nutritional imbalances when grazing monocultures (e.g. minerals in wheat) • Management difficulty, high intakes can quickly reduce shelter value
Hessian, hay bales or man-made structures	• Effective wind break • Flexible construction • Baled straw can be an inexpensive cropping by-product	• Small scale • Often solid, less effective in improving ewe and lamb interaction than are shrubs • Solid structures can create a vortex and cause erosion

(Egan *et al.* 1972). Sheep can also intermingle with the vegetation and find both isolation and protection. Shrubs require a medium- to long-term commitment, although are easier to remove than are large trees and are more suitable for low-rainfall regions where tree growth is slow and perennial grasses and legumes have poor survival. Shrubs such as saltbush and tagasaste have an additional benefit of growing on land that is too saline or sandy for conventional pasture and crop species. Adoption therefore has a lower opportunity cost and the shrubs provide environmental benefits such as reduced salinity and erosion (Masters *et al.* 2005).

Perennial grasses, usually overgrown and mature to form tussocks, have been well investigated and reviewed (Pollard 2006). A 50% reduction in wind speed at lamb height was reported by Cresswell and Thompson (1964); similarly, Lynch and Alexander (1976) reported a reduction of 30–100% at sheep (45 cm) and lamb (10 cm) height in the lee of tall-grass shelters. While perennial grasses can be very effective, they may fail to grow or regenerate during drought conditions and then provide little shelter (Robertson *et al.* 2011). Perennial legumes have not been investigated to the same degree as have grasses. For both, management will need to be considered, because forage species and accessions within species differ in their nutritional value and growth rates according to planting density, cutting height and cutting frequency (Bell *et al.* 2018; Norman *et al.* 2021).

Vegetative crops are usually grazed during late gestation when crop height is short, and the livestock are removed when stem elongation begins. Longer grazing times with taller crops is an option that would provide both feed and a potential windbreak. In one study, grazing an oat crop that was planted in laneways to allow twin lambs to follow their mother, a non-significant increase in lamb survival was reported compared with a lambing group that grazed pasture (Glover *et al.* 2008). This was during mild winter conditions, with only a 6–7 cm increase in height of the crop compared with pasture. Anecdotal reports from producers suggest that if the crop is too high, lamb mortality increases due to mismothering, with ewes losing their lambs in the crop, or due to exposure as the ewes lamb along the fence line outside of the shelter provided from the crop. Winter crops will provide no shade benefits during summer and there is no information available on sheep grazing summer crops.

Man-made physical barriers can be highly effective. One metre high hessian rows placed 20 m apart and aligned perpendicular to the prevailing wind significantly reduced wind speed (70–83%) and chill index (5%) over a distances 2–10 times the height of the barrier (Broster *et al.* 2017). Installation can be expensive and time consuming and man-made shelter is better suited to small-scale lambing paddocks. Baled crop stubbles or hay offer another opportunity for shelter and may be less expensive and easier to construct. Many of the options for man-made wind breaks are short and would provide little shade.

Placement

Planning begins with an understanding of the wind across different seasons, with shelter placed to provide protection from the prevailing wind at the time of the highest risk to livestock. Thus, if the prevailing wind is from the west, shelter should be on the western side of the area to be protected (Dronen 1988). This is not always a simple task as climatic data for the time of lambing are not always available and winds that are light or warm will have little impact on survival. This can be addressed by constructing a wind rose to describe the prevailing winds during periods of low temperature and rain (McCaskill and Clark 2007). To minimise wind, shelter should not be planted on ridges as placement there accentuates air flow and may increase wind on the lee side. This is less relevant where slopes are less than 8% (Finch 1988).

There is support for an alternative or complementary approach that is based on an understanding of where ewes choose to lamb without shelter. Alexander *et al.* (1990) observed that Merino ewes tended to seek isolation in preferred lambing areas at higher elevation within a paddock. This was consistent across years. British breed ewes did not show the same tendency and lambed on the edge of the paddock or in association with features such as rocks and trees. The authors acknowledged the confounding factors such as prior history and management of the animals, weather during the studies, paddock size, topographic and other features that make each paddock unique but, even allowing for these, the non-random distribution of birth sites over several years suggested that providing shelter at sites that are naturally selected by the ewes could be effective.

A combination that addresses prevailing wind and weather together with preferred lambing sites may offer the best option.

Design

Shelter value is influenced by the height, density and length of the windbreak (Caborn 1957). On the windward side of a windbreak, wind-speed reductions are measurable upwind for a distance of two to five times the height of the windbreak. On the leeward side, wind-speed reductions occur up to 30 times the height, downwind of the barrier. If the windbreak is very dense, low pressure develops in the leeward side, pulling air downward, thereby creating turbulence and reduced protection (Caborn 1957). A shelter density of 50–80%, with a row spacing of 1–2.5 m for shrubs and 2–6 m for trees has been recommended as the most desirable windbreak density for livestock (Dronen 1988; Finch 1988). This density provides a permeable barrier and more protection; there is a faster recovery in wind speed from a dense shelter belt (Gregory 1995). For shrubs, a complex construction has better shelter effects than does a uniform monoculture (Wu *et al.* 2015). Where shelter is provided in rows, spacing between grass rows of 20–240 m has been effective. If trees or shrubs are used, the protection (and therefore row spacing) can be estimated from the height, or, if the rows are to be combined with alley farming, (Kang *et al.* 1990), machinery width needs to be considered. There is a trade-off between row width and ability to maintain a high-value understorey for production and provision of a diverse diet.

Utilisation

As well as managing shelter to suit livestock, options exist to manage livestock to optimise the potential benefits of shelter or the risks of cold and heat. For example, pregnancy scanning ewes and allocation of twin lambers to shelter is a better strategy than random allocation, particularly if available shelter is limited. Synchronisation of lambing with growth of crop or pasture shelter may improve both shelter and forage supply, and time of shearing may be used to influence shelter use in high-risk environments.

Ancillary effects of shelter and shade

There is a range of secondary benefits from the provision of shelter and shade. Some of these have been identified and quantified, others have not.

Drought and out-of-season feed

Edible shelter and shade have the potential to provide feed during seasonal fluctuations in plant growth and during drought. To be of value, the plants need to be accessible, palatable and be a source of nutrients. Shrubs have long been considered a potential forage source for grazing ruminants, particularly in dry and seasonally variable agricultural zones (Lefroy *et al.* 1992; Le Houérou 1992). Up until the

1990s, only leucaena (*L. leucocephala*) and tagasaste (*C. palmensis*), both species introduced into Australia, were options that had been commercially cultivated (Lefroy *et al.* 1992). Most of Australia's sheep are in the south of the country where only dry and dead forages are available for grazing over summer. Hay or grain supplements are often required at this time. Within this region, tagasaste can partially fill the summer feed gap and is equivalent to or better than production from dry feed and supplements (Oldham *et al.* 1991). Lefroy *et al.* (1992) suggested there are several million hectares of infertile sandy soils in southern Australia where tagasaste could fill a niche.

More recently there has been renewed interest in other shrubs for forage and shelter. Revell *et al.* (2013) measured the nutritive value of 39 Australian native shrub species and found that many had digestibility and CP content high enough to support growth in young sheep. In subsequent experiments, sheep that grazed shrub rows with annual pasture between rows increased liveweight while animals grazing dry pasture alone maintained only weight (Revell *et al.* 2013). The authors suggested that shrubs provide a timely and predictable supply of limiting nutrients with additional benefits in gut health, shade and shelter and could make a valuable addition to the feed base in low- to medium-rainfall zones in southern Australia. The shrub of most interest is saltbush (*Atriplex* spp). Saltbush is a salt-tolerant and drought-tolerant shrub that has been investigated over many years as a feed source and drought reserve in the rangelands (Wilson 1994). The shrub has come back into focus as an option to revegetate saline land in the agricultural zones (Norman *et al.* 2013). *Atriplex nummularia* has now been through a plant-improvement program to develop a cultivar (Annameka) with improved biomass production, palatability and nutritive value relative to most of the wild varieties (Masters and Norman 2010; Norman *et al.* 2016). The availability of these and other halophytic and drought-tolerant plants (Norman *et al.* 2013) provides an opportunity to use land with a low production potential to provide shelter, shade and drought feed.

Vegetative crops are not a drought feeding option as they would usually fail to grow. However, early growth of winter crops at the end of the annual seasonal drought in Mediterranean environments provides an early season feed supply and allows for deferment of grazing in pasture paddocks (Thomas *et al.* 2015).

Pasture and crop production

Providing shade and reduced wind can improve both the rate of growth and the length of the growing season in crop and pasture production. In cold environments, a reduction in wind speed will result in higher temperatures in sheltered plants, leading to improved growth and reduced risk of frost damage (Bird *et al.* 1992). Lower wind speed also means reduced physical damage such as shaking, leaf stripping or abrasion from blown soils (Nuberg 1998). Shaking reduces cell expansion and growth and has been associated with a 20% reduction in leaf extension area in tall fescue (*Festuca arundinacea*) (Grace 1988). Over the longer term, a reduction in wind speed may reduce evapotranspiration and slow the depletion of soil moisture (Ritchie 1988). This is not a consistent observation as higher wind speed can also lower soil temperature and reduce soil moisture loss (Gregory 1995). Short or prostrate plants are more tolerant of wind damage than are tall erect plants. The extent of the benefit will be dependent on the reduction in wind and, hence, the height and proximity of the shelter. Trees provide wind protection over a larger area than do shrubs, grasses or artificial barriers, with protection up to 10 times the height of the trees. Only in plants that are very close to trees will growth be reduced due to shading and competition for soil moisture (Radcliffe 1983). Increased pasture and animal production have been reported in small, sheltered plots, possibly by changing the water balance within the plants. The benefits were most apparent at high stocking rates (Lynch and Donnelly 1980). Shelter improved the regrowth of pasture grasses in Scotland (Russell and Grace 1979) and improved the growth and, in some studies, the nutritive value of pasture plants in New Zealand, Netherlands, Hungary, USA and Canada (Radcliffe 1983).

Many of the experiments describing the advantages of windbreaks on crop and pasture production have been conducted in cold climates; the benefits in warmer rain-fed cropping systems common in Australia are more variable (Baker *et al.* 2018). There is consistently a loss of production in the competition zone close to the shelter and this is sometimes but not always exceeded by gains in the sheltered zone. In the 12 Australian studies summarised by Baker *et al.* (2018), all showed a net increase in production under some but not all conditions, often in dry years in areas exposed to high winds. The authors suggested that windbreaks may increase in importance with expected hotter and drier climates with more extreme weather events.

Shelterbelts in close proximity to pastures and crops may also act as reservoirs for predatory insects. Tsitsilas *et al.* (2006) reported low numbers of pest mites and lucerne fleas in shelterbelts and increased numbers of predatory mites and spiders both within shelterbelts and nearby pastures. Although others have reported similar benefits (Landis *et al.* 2000), this is not always the case (Dix and Leatherman 1988).

In hot environments, shading and windbreaks will reduce the deleterious effects of higher plant temperature. Shelter may also reduce evapotranspiration and improve the conservation of soil moisture (Gregory 1995).

Landscape health

The role of shelter plants in protecting soils and vegetation has been well summarised in previous reviews (Ritchie 1988;

Bird *et al.* 1992; Lefroy *et al.* 1992; Nuberg 1998). The review by Bird *et al.* (1992) is now 30 years old, but the problems are now worse and solutions more urgent. The authors cited vast areas in Australia's south where wind and water erosion, dryland salinity, soil acidification, loss of soil structure and nutrients and water repellence are causing landscape degradation, costing millions of dollars. Others have described the disproportionate losses of nitrogen, phosphorus and organic carbon in eroded dust (Leys *et al.* 1997). The loss of trees contributes to much of this degradation and means reduced soil organic matter and water-holding capacity and loss of topsoil. Similar problems have been described in the USA, Canada, Russia, China, and Europe (Bird *et al.* 1992). Trees within paddocks also have the potential to provide habitat to complement remnant vegetation in the agricultural landscape and provide transport corridors for birds (Law *et al.* 2000; Fischer and Lindenmayer 2002). The loss of trees is not the only problem, with the loss of shrub and other natural vegetation from arid and semi-arid environments causing similar land and habitat degradation.

Shelterbelts of trees, shrubs, and perennial grass tussocks will not alleviate landscape degradation but can contribute through the modification of wind and water movement. Even single rows or small belts of tall trees can have an impact on wind speed over a large area. Shrubs and grasses will modify wind speed over a much smaller area but, used strategically, can significantly influence water movement and accumulation. Shrubs, trees, and deep-rooted perennial plants have been used to reduce inundation, waterlogging, and flooding, while salt-tolerant shrubs are grown to provide livestock feed and shelter on the saline valley floors (Masters *et al.* 2006).

The configuration of tree and shrub revegetation that is best for landscape health may not also be the best for livestock. For example, the inclusion of livestock may decrease the effectiveness of the trees in reducing wind by reducing height and density of the plants (Bird *et al.* 2007); nevertheless, the publications that have focussed on shelter and shade indicate collectively that there can be benefits for both livestock and the landscape. This should be a consideration in siting and designing shelter and shade.

Practicality and economics of shelter and shade establishment and use

Disadvantages of shelter

The low adoption of shade and shelter indicates that for many sheep producers, active establishment is not a priority. This would indicate that they are not convinced that the advantages outweigh the perceived disadvantages. Disadvantages include the following:

- Reduced flexibility of land use
  - The removal of some land from crop rotation with the establishment of trees, shrubs, and even grass hedges
  - The medium–long-term commitment in the establishment of trees, shrubs and structures can reduce production and management flexibility
  - Physical interference in the use of some of the large semi-autonomous cropping machinery that is used during harvesting, seeding, and spraying
- Loss of productive land
  - The loss of land for crops or pasture. Potential reduced stocking rate
  - The lower productivity of crops and pasture close to shelter due to shading and competition
  - Increase weed-control costs (Walpole 1999)
- Cost of establishment and maintenance
  - Costs for plants, seeds, seedings, fertiliser, planting, management and fencing
  - Additional management time required to ensure appropriate grazing and livestock nutrition
  - Cost of pruning and thinning
- Soil attributes
  - Compaction and pugging around shelter and shade
  - Nutrients relocated to shade and shelter
- Uncertainty regarding use by sheep and production benefits
  - Over-utilisation of lambing paddocks, with wind speed reducing shelter by over-stocking the density of ewes can lead to reduced lamb survival (Robertson *et al.* 2012)

Parris *et al.* (2011) acknowledged the risk that corridor plantings can cost producers in loss of income, on-going management costs, potential opportunity costs of unforeseen future opportunities, and significant upfront transaction costs. While many of these disadvantages can be addressed, a medium–long-term farm plan is required, together with a detailed land capability assessment.

Economic evaluation of shelter and shade

Estimating the value of shade or shelter to an enterprise or a whole-farm business is particularly challenging, including factors such as existing (remnant) vegetation, its location in relation to pastures, aspect, slope and suitability to provide the primary livestock needs for protection from either the wind or sun, or both. In certain locations, the economic benefit for animal production from shade or shelter will be upscaled when the structure provides adequate protection at the time when reproduction is sensitive to climatic perturbation.

McEachern and Sackett (2008) used a gross-margin analysis to conclude that the cost of the establishment of shelter for the purpose of improving lamb survival was not economically justified. Subsequently, Young *et al.* (2014)

concluded that the McEachern and Sackett (2008) analysis had assumed large costs for establishment, fencing, grazing deferment and stocking rate, with only modest benefits in lamb survival. Young *et al.* (2014) then published a more comprehensive whole-farm economic analysis that focussed on the use of tall-wheatgrass shelter to improve the survival of winter- and spring-born twins in south-eastern Australia. The study evaluated different flock structure, twinning, mortality, and commodity-price scenarios (2500 scenarios were tested in total). Under all scenarios, the provision of shelter was profitable, ranging from a few cents per ewe to A$11.35 per ewe. The most beneficial scenario was associated with a 35% increase in the weaning rate, while the least beneficial was associated with a 1% increase. The modelling did not allow for any improvement in the survival of single lambs or for any non-livestock benefits. The limitation of this analysis was that it was based on one location and therefore one climate/production dataset.

Other studies have assessed the economic benefits of trees and shrubs for out-of-season forage supply. A plantation of tagasaste shrubs was shown to be a profitable substitute for hand-feeding grain in autumn (Oldham *et al.* 1991; Lefroy *et al.* 1992) and farming 10% of a typical central-wheatbelt crop and livestock property in Western Australia with shrubs has been predicted to increase whole-farm profit by approximately 24% (Monjardino *et al.* 2010). In Tasmania, measured increases in pasture production were used to model the gross margins from the integration of trees and livestock. Gross margins from a 2-row tree belt that accounted for values for amenity, carbon sequestration, timber production as well as pasture and livestock were 41–74 A$/ha.year more than for a pasture-only scenario (Mendham 2018). Similarly, Walpole (1999) reported that gross margin of pasture outputs was maximised when the proportion of the tree area across a farm was 34%. The same group (Walpole *et al.* 1999) surveyed north-eastern Victorian and New South Wales (NSW) Murray-region landholders to report the on-farm benefits and costs associated with remnant native vegetation. Most NSW landholders (>60% of survey participants) were sheep, cattle and cropping enterprises. For these landholders, the most important economic benefits of remnant native vegetation were stock and crop shelter, while for all respondents, the cost of weed control was the major economic cost. Among the NSW participants, 84% used the remnant vegetation for shade and shelter and 95% identified the benefits of remnant native vegetation included its aesthetics and 73% identified benefits for increased stock production. From this work, Walpole *et al.* (1999) estimated that the value of shade and shelter was A$4.41/ha and A$9.54/ha for reduced land degradation. Other benefits, such as cleaner water, nutrient cycling and habitat for pest-controlling predators were identified but by fewer respondents (49%, 42% and 61% respectively).

There may be additional benefits when shade and shelter are provided by native vegetation. Native vegetation underpins many social and economic aspects of Australian society and has a crucial role in sustaining ecosystem function and processes (Council of Australian Governments 2012). Costanza *et al.* (2014) estimated that biodiversity contributed more than US$125 trillion of value to the global economy in 2011. However, trends in Australia have shown a substantial reduction in native vegetation. For example, the Victorian 2018 State of the Environment Report (Commissioner for Environmental Sustainability Victoria 2018) claimed a total loss of 567 913 ha of landscapes supporting native vegetation between 1990 and 2015, primarily from urban development, timber production and agriculture. Some of these losses were native scattered trees (149 063 ha, approximately 27% lost) and native shrubs (48 642 ha, approximately 29% lost).

The value of natural forms of shade and shelter will also have amenity values and may improve real estate value by between 10% and 30% (Oates and Clarke 1987). Those authors were unable to place a value on shade, although recognising its many benefits. The manual *Towards sustainable grazing* (Mason *et al.* 2003) claims the most successful grazing businesses deliberately incorporate management of environmental issues into their core operation, such as increasing biodiversity using native species and aiming for a minimum 10–15% of the property with conservation as the priority, or including at least one patch of remnant vegetation ≥10 ha in size. However, they also recommend that biodiversity initiatives should be focused on the less productive parts of the farm (Mason *et al.* 2003), which is likely to place quality shelter in places away from quality pastures.

Recommendations for the design and use of shelter and shade – current knowledge base

The assessment of available information indicated that shelter and shade will improve welfare and profit when they are used in locations with a high risk of cold when ewes are lambing or after shearing, or high risk of heat during joining, gestation, and the perinatal period. Further, changing microclimate can lead to other productivity and environmental benefits.

Options that are based on the best current knowledge include the following:

- Shrub belts, preferably using shrubs with a nutritional value to complement pasture and of varying height and palatability. Such belts need to be designed to obstruct the most lethal prevailing wind and consideration should be made to growing them in soils that are unsuitable for crops or at risk of erosion and salinity. Optimum planting would include locally adapted or indigenous species. These shrub belts will also provide shade and a feed supply during dry seasons and droughts.

- Trees, even as a single row, will reduce wind chill, provide shade, and deliver multiple crop and environmental benefits over a paddock or even a landscape scale. To maximise the ancillary benefits, locations should be selected that maximise wind interception.
- Perennial grass hedges and possibly herbaceous legumes are highly effective in improving lamb survival in cold environments. They provide limited feeding value or shade and have traditionally been used on a small scale. This small scale reduces the potential for landscape benefits on erosion and salinity. Grass hedges may be best suited for designated lambing paddocks, particularly those paddocks that are used with twin-lambing ewes.
- Vegetative crops have the theoretical capacity to meet many of the requirements for shelter but not shade. They may be useful and allow flexibility but are so far unproven. Establishment is linked to rainfall and sowing time; producers will need to manage lambing time to match predicted growth patterns.

General principles that apply to all types of shelter include the following:

- A shelter density of 50–80% or a height that will allow some permeability and visual contact between animals.
- That they be located on the side of the paddock perpendicular to the prevailing wind during lambing and away from ridges, particularly in steep terrain.

Extension material on the benefits and costs of shelter and shade will need to include region-specific information on ancillary benefits in plant production and landscape health.

Knowledge gaps – research recommendations

Despite many experiments demonstrating multiple benefits to the planting of shelter and shade for sheep, the practice has been poorly adopted. There are many knowledge gaps, and it is very likely that these are associated with uncertainty and the low adoption.

The following gaps are apparent from this review:

- There is uncertainty around the lamb-survival responses in different regions and climatic conditions. This could be addressed by extending the analysis of Broster *et al.* (2012*a*) or McCaskill and Clark (2007) to cover all of the major sheep growing climatic zones and lambing strategies. Such information would provide confidence around the potential benefits for decision making.
- Many of the experiments on cold stress have been in small paddocks, leaving a gap in our understanding of the voluntary use of different types of shelter by sheep in large paddocks. This should be combined with measurement of the behaviour of ewes and lambs and their interaction within shelter. This knowledge is required for both the justification and design of shelter in commercial-sized flocks.
- As part of assessing the use of shelter in a commercial setting, the potential to attract ewes to shelter through the provision of macro and micronutrients and nutraceuticals, should be explored. Such studies should incorporate areas of palatable and unpalatable species.
- Alternative shelter options such as vegetative crops and perennial pasture plants offer options that can be utilised within a routine crop and pasture rotation program and should be investigated.
- The consequences of heat stress on a full production cycle are not well understood. Short-term heat events can alter fertilisation, implantation (returns to service), fetal development and lamb survival. These effects will be insidious and easily missed over an annual production cycle.
- Technology can and should be used within experimental studies to define changes in physiology, stress, and behaviour as the basis for change in production and welfare.
- Collection and compilation of information to allow system benefits (production and ecosystem function) to be modelled and valued across farms and landscapes.

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Author affiliations

[A]School of Agriculture and Environment, Faculty of Science, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.

[B]CSIRO Agriculture and Food, Private Bag 5, Wembley, WA 6913, Australia.

[C]College of Science, Health, Engineering and Education, Murdoch University, Murdoch WA 6150, Australia.

[D]School of Human Sciences, Faculty of Science, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.

[E]New South Wales Department of Primary Industries, Cowra Agricultural Research and Advisory Station, Cowra, NSW 2794, Australia.