Milestone report

Project code: L.LSM.0024

Prepared by: William van Wettere, Sam Culley, Kathy Gatford, Karen Kind, Stephen Lee, Stephan Leu, Alyce Swinbourne, Seth Westra, Peter Hayman, Dave Kleemann, Jen Kelly, Dane Thomas, Alice Weaver and Simon Walker
The University of Adelaide and The South Australian Research and Development Institute

Date published: 10th February 2020

PUBLISHED BY
Meat and Livestock Australia Limited
Locked Bag 1961
NORTH SYDNEY NSW 2059

Stage 2: Effects of heat stress on reproductive performance of the Australian sheep flock

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

This publication is published by Meat & Livestock Australia Limited ABN 39 081 678 364 (MLA). Care is taken to ensure the accuracy of the information contained in this publication. However MLA cannot accept responsibility for the accuracy or completeness of the information or opinions contained in the publication. You should make your own enquiries before making decisions concerning your interests. Reproduction in whole or in part of this publication is prohibited without prior written consent of MLA.

Executive Summary

Between November and March (spring to early autumn), it is common for cycling and pregnant ewes as well as working rams to be exposed to high ambient temperatures which profoundly challenge homeothermy, wellbeing and reproductive function. Based on the literature, ewes experiencing heat stress during the 6 – 10 days around the time of joining experience reductions in oocyte quality, fertilisation and embryo survival, with ram fertility reduced during the 9 – 50 days following a heat stress incident. Importantly, data from two large, comprehensive, Australian field studies demonstrated that the number of ewes lambing and the number of lambs born per 100 ewes joined correlated negatively with the number of days per week during the mating period when ambient temperatures were ≥ 32.2 °C. We used the equations developed from these studies in conjunction with Australian Gridded Climate Data and data from 26 sheep producing regions to model the effects of heat stress (days > 32 °C) around joining on the number of lambs born and the number of ewes lambing. Overall, based on the sites investigated and their current seasonal joining patterns, it is estimated that 2.1 million potential lambs are lost due to heat stress under the current climate, with this number likely to increase to 2.5 and 3.3 million should a 1 °C or 3 °C increase in Australian temperatures occur. In addition, heat stress during gestation is likely to retard conceptus development, particularly for flocks mated in spring/summer, with the potential to reduce lamb birthweights by 0.6 – 1.4 kg, and decrease survival to weaning by 20 – 30%. The profitability of the Australian sheep flock is, therefore, extremely vulnerable to heat stress.

The economic cost of heat stress was calculated by comparing the profitability without heat stress against the current and projected levels of heat stress without changing the number of animals or the amount of pasture production. Two levels of economic impact were estimated; (1)a robust model, based solely on the effect of heat stress on the reduction in lambs born and ewe lambing per joined ewe; and (2) a best bet model, which included the cost of reduced birthweight due to sustained pregnancy heat stress. The current national cost of heat stress is estimated to be $97 million annually for the robust model or $168m for the best bet model (lamb price $6/kg), which increases up to $166 million or $278 million annually in a climate scenario +3 °C. The reduction in profit per ewe in the national flock due to heat stress averages $2.91 for the robust model and $5.04 for the best bet model (lamb $6/Kg, current climate). However, it is more informative and appropriate to consider how the reduction in profit per ewe differs across the regions. The cost of heat stress varies from $0 up to $15.50 per head depending on the region, with the maximum $ impact increasing to $23.70 should temperatures increase by 3°C. Forty percent of the flock has a cost of $1/ewe or less and another 40% of the flock has a cost of $10/ewe or more. Those regions above $10/ewe incur the majority of the national cost. In these regions, an amelioration strategy that halves the cost of heat stress will still be profitable if the cost to implement the strategy is $5/ewe.

The second component of the analysis focused on strategies that could be developed through research and development and included shelter, nutrition, containment mating, mating protocol, time of shearing, time of lambing and genetic selection. It was very difficult to quantify the amelioration strategies because there is very little data on which to base what is required or the effectiveness of each strategy. However, some best estimate of the implementation costs varied from $0 up to

$10/ewe and the expected level of amelioration varied from 0 up to 100%. Combining scenarios for the proportion of the impact ameliorated and the on-farm cost of implementing the technology allows generation of the annual research budget that would return a benefit cost ratio (BCR) of 4. The amelioration calculations provided a range of values with which to interpret the reverse benefit cost analysis and if it is expected that strategies that are 50% effective and cost $5/ewe could be implemented then an annual budget of $500 thousand would deliver a BCR on funds invested of 4.0. The budget is very sensitive to the proportion of the heat stress ameliorated especially as the on-farm implementation cost increases.

The need to develop effective, and commercially adoptable strategies to alleviate the impacts of heat stress on the Australian sheep flock are clear. The outcomes of our literature review and the impacts of heat stress on the number of lambs born and, potentially, surviving to weaning were discussed with the SALRC SA regional committee and consultants on the 13th December 2019. There was a sense of urgency from all members of the committee for the need to provide producers with insights into the potential impacts of heat on sheep reproduction, to identify and implement existing mitigation strategies on-farm, and to initiate research in areas where knowledge is lacking. Based on the outcomes of these discussions, we developed this document, which contains a detailed description of the existing gaps in our understanding of how, and to what extent, heat stress impacts reproduction of the Australian breeding flock. This document also details what research is required to develop practical strategies which can be adopted either in isolation or as part of a management package to reduce the impact of heat stress on ewe and ram reproduction, as well their progeny.

The following knowledge gaps were identified. There is minimal data describing the impacts of the climate experienced by pasture and rangeland sheep on their homeothermy, behaviour, resource use and reproduction. This applies to ewes at all stages of the breeding cycle (before joining through to weaning), rams, and the progeny born to heat stressed ewes and rams. The potential to ameliorate the impact of heat stress on sheep through husbandry changes, environmental modification and selection for heat resilience is not known. Based on these knowledge gaps, priority areas for research focussed on understanding the impacts of heat stress on reproduction of the Australian sheep flock and mitigating the risk for producers were developed, and are summarised below.

Research should be conducted to establish the impact of heat stress on reproduction of the Australian breeding flock through increased understanding of the physiological, homeothermic, behavioural and reproduction responses of individual sheep to the climate and environment experienced under field conditions. Particular priority areas include investigation of microclimates within pastures and rangelands and their impact on homeothermy and reproductive function. Conducting controlled studies to determine the impact of acute, chronic and intermittent exposure to heat stress conditions on the components of ewe and ram fertility. Combining retrospective and prospective reproduction data with BoM climate data and homeothermy data from sentinel sheep, to establish critical THI thresholds (level and duration) above which reproductive outcomes are negatively impacted. Understanding how heat stress during key periods of the reproductive cycle affects progeny performance should also be a research focus.

It is also vital to develop effective amelioration strategies which can be adopted by producers to reduce the risk of reproductive failure associated with heat stress. This body of research should seek to develop nutritional strategies which prevent heat induced suppression of reproduction, facilitate homeothermy, and maintain feed intake and digestive health of heat stressed sheep. Establishing the impacts of shade, as well as the optimal type of shade (i.e. trees, shrubs or artificial structures) is also important. The benefits of trees and shrubs as sources of shade also include shelter for cold conditions, biodiversity and carbon sequestration, thus aligning with the need to reduce lamb mortality during cold periods and the Carbon Neutral by 2030 (CN30) initiative. In addition, the benefits of modified mating protocols and shearing times as strategies to mitigate the risk of heat stress induced reproductive failure should be investigated, as these strategies may be readily incorporated into current management systems. The increased use of confinement feeding over summer presents further opportunities for natural and artificial shade, and adoption of more sophisticated nutritional strategies. In addition to such management strategies, amelioration may be possible through selection to increasing heat resilience of common sheep breeds. Research should, therefore, be conducted to identify and measure parameters of homeothermy and to determine their repeatability both within individuals, as well as between flocks and breeds. This would then allow improvement of thermo-tolerance through marker-assisted genetic selection, which has been successful in cattle.

One approach to ranking research focussed on protecting the sheep industry from the detrimental impacts on heat stress is to do so based on the following high priority outcomes; (1) increasing fertility of ewes and rams exposed to heat stress; (2) increasing birthweight and survival of lambs born to ewes exposed to heat stress during pregnancy; (3) reducing the impact of heat stress on progeny performance; and (4) optimising commercial adoption of mitigation strategies through increased understanding of the extent of the problem, and commercial validation of any mitigation strategies. Based on this, the four research priorities have been ranked in order of urgency, practicality and likely time to outcome delivery.

1) Establishing mitigation strategies which promote homeothermy and reproductive function of ewes and rams under thermal strain (i.e. nutrition, shade, wool cover, mating protocols)
2) Understanding the impact of ambient conditions on the behaviour, resource use and fertility of sheep under typical production systems, and identify differences between individuals (behavioural, physiological, molecular) in their ability to thermoregulate and maintain reproduction under thermal strain.
3) Modifying the environment to reduce the severity of thermal strain (use of shade, establishing cooler micro-climates, establishing THI thresholds, adoption of containment housing systems)
4) Selection for physiological and behavioural adaptions which promote heat resilience without impairing productivity.

It is worth noting that the achievement of most of these research outcomes would be facilitated by the development of non-invasive sensors which allow temperature, behaviour and fertility to be monitored in free-ranging ewes and rams. Such sensors may have commercial benefits, particularly for rams, thus enabling producers to intervene when ram performance is compromised, and when establishing the impacts of heat stress on progeny performance. Secondary stages of any research should involve commercial validation in a range of production systems (containment housing, pasture and rangeland), with consideration given to the development of production demonstration sites, resulting in wide scale commercial adoption within 5 to 10 years.

In conclusion, it is clear that heat stress has a significant, negative impact on the reproductive performance of the Australian sheep flock, with the annual cost of this source of reproductive wastage calculated at $97 million (robust model; fewer lambs born) or $168 million (best bet model; fewer lambs born and weaned) annually. It is expected that this will worsen under projected climate changes, with the annual cost increasing to $166 million (robust model) or $278 million (best bet model) in a climate scenario +3 °C. Based on the considerable gaps in current understanding of the impact of heat stress on sheep behaviour and reproduction, it is also clear that a significant body of research is needed to develop husbandry practices which protect the Australian sheep flock from the significant risk of reproductive failure.

Table of Contents

1. Summary of the effects of heat stress on reproduction of ewes and rams

Both short- and long- term exposure to high ambient temperatures and humidity significantly impair the fertility and fecundity of ewes, and decrease semen production and quality in rams, resulting in fewer lambs born per ewe mated. Furthermore, reductions in lamb birthweight and ewe mammary development resulting from heat stress during pregnancy, are likely to significantly decrease lamb survival and weight at weaning.

For the purposes of this review, the reproductive cycle of the ewe was separated into three broad periods: oestrus/mating, pregnancy and lactation. The impacts of heat stress during these periods on ewe and ram reproduction are summarised below. However, there are several limitations to the currently available evidence in this field. Firstly, the majority of work in this field involved the use of hot-rooms, where the severity and duration of thermal stress experienced was not reflective of temperature and humidity typical of the Australian climate. Secondly, both chronic and acute heat stress are common during summer and yet the relative impacts of each on reproductive function remain unclear, as are the effects of acclimatisation. Equally important, the additive effects of other stressors which sheep typically experience during summer, including nutritional deprivation and walking long distances, were also rarely taken into account. However, there is general agreement that reductions in feed intake account for only a relatively minor portion of the negative effects of heat stress on reproduction and lactation.

1.1. Heat stress around mating decreases ewe reproduction

In field studies, high ambient temperatures (≥ 32 °C) during the mating period adversely affect ewe fertility, resulting in fewer lambs born and fewer ewes lambing. This effect appears to be manifested around the time of fertilisation and early embryo development. On the other hand, the incidence of oestrus and ovulation rate are each reduced when heat stress is experienced five days prior to the event. Studies conducted to examine the effects of acute temperatures (using hot-room conditions) clearly identify the reproductive processes that are vulnerable to hyperthermia. These include the length of the oestrous cycle, duration of oestrus, quality of the ovum and its ability to fertilise as well as the survival of the embryo, particularly during the early stages of development. The period during which heat stress is most destructive extends from three days before oestrus until three days after oestrus, but continues to worsen with lengthening duration of heat stress up to at least the ten days surrounding oestrus. The oestrus expression and duration are more affected the earlier heat stress is applied, whilst ovum quality and fertilisation are most vulnerable when heat is applied around the time of oestrus, and embryo wastage is greatest when heat stress is applied on the day of oestrus and the ensuing five days. A number of these hot-room studies used extremely high temperatures (approximately 40 °C); however, reductions in ovum quality, fertilisation rate and embryo survival were also observed in ewes housed in hot-rooms at temperatures of 32.2 °C. This is consistent with evidence from field studies where ewe fertility is negatively correlated with the number of days ≥ 32 °C occurring during the mating period.

The identification of these critical periods provides a useful basis for the development of strategies for the future management of ewe flocks as ambient temperatures increase. However, it is noteworthy that in the few hot-room studies where high temperatures were moderated by diurnal relief, the negative impacts on reproductive wastage were less severe. This indicates that extreme weather events (e.g. prolonged heat-waves without some diurnal relief) during the mating period are likely to cause the most significant reductions in flock reproductive performance.

1.2. Heat stress around mating impairs ram fertility

Experimentally exposing the testes of rams to an increased heat load reduces semen quality. However, in contrast to the immediate effects of hyperthermia on ovum quality, effects on semen quality are delayed. Reduced sperm motility and increased morphological abnormalities are not observed until approximately 9 days after heat exposure. These negative effects can be sustained for 3-5 weeks, with the most significant effects occurring 14-21 days after heating. Sperm numbers can also be reduced and may not return to normal levels until 50-60 days post-heating. Consequently, this reduction in semen quality can affect the fertility of the ram from approximately 9 until 50 days post-heat event, with reduced fertility resulting from increases in both fertilisation failure and embryonic loss. Importantly, the effects of heat exposure on spermatogenesis, sperm quality, and hence ram fertility, are closely related to the increase in testicular temperature. There is variation between rams in the capacity to regulate scrotal temperature, with some rams able to maintain scrotal temperatures 2-3 °C lower than others. Scrotal thermoregulatory capacity, its variation between rams and the level of heat exposure required to elevate testicular temperature above acceptable levels, has been little studied under Australian field conditions.

Furthermore, the application of these results to field conditions, and the ability to extrapolate the impacts on the productivity of the Australian flock, are complicated due to; (1) the extent and duration of heat stress studied experimentally will often differ from conditions typically experienced in the field; and (2) the delayed impact of heat stress on sperm quality may make it difficult to identify the effects and timing of heat stress under field conditions.

1.3. Heat stress during pregnancy and lactation decreases birthweight, lamb survival and milk output

The impacts of heat stress during pregnancy on fetal and lamb development are restricted primarily to studies using hot-rooms. In these studies, pregnant ewes were typically exposed to prolonged periods of hot days (ranges: 6 – 18 h per day, 35 – 44 °C and temperature humidity index (THI) of 83.2 to 97.0) with cooler nights (ranges: 6 – 18 h per day, 16.4 – 35.0 °C, THI of 38.3 – 83.5) similar to those experienced in the field. However, in the majority of these studies heat stress conditions were maintained for 50 to 150 days, a continuity of heat stress which is unlikely under normal climatic conditions. Despite this, it is clear that even several hours of heat stress per day are sufficient to increase fetal temperature and reduce blood supply to the fetus. Importantly, prolonged periods of heat stress at any stage of pregnancy consistently reduced lamb weight and viability at birth, thus decreasing their chance of surviving to weaning. Similar to rams, ewes vary in their ability to thermoregulate when exposed to heat stress conditions, with lower core temperatures during periods of heat stress associated with heavier lamb birthweights and increased lamb survival. Phenotypic variation in lambs born to heat-stressed ewes is also probable, and likely to be sufficient to alter their post-natal performance and productivity. Studies in cattle indicate that milk production may also be impaired by gestational heat stress, although this has not been studied in sheep. Based on evidence from dairy cattle and sheep, exposure to THI greater than 65-68 during lactation may also impair milk production of the Australian sheep flock.

1.4. Heat stress in the field reduces reproductive performance of the Australian breeding flock

The majority of Australian flocks are joined between November and March, the period when temperatures are at their highest, and mean daily maximum temperatures regularly approach and exceed 35 °C. It is evident from the extensive studies of Lindsay et al. (1975) and Kleemann and Walker (2005), of 53 and 68 flocks respectively, that reproductive performance of Australian sheep flocks is adversely affected by elevated temperatures during the joining period. In both studies, ewe fertility (number of ewes lambing per 100 ewes joined) correlated negatively with the number of days per week during the mating period when ambient temperatures were ≥ 32.0 °C. Further, a negative correlation between heat stress during mating and the number of lambs born per 100 ewes joined was also reported by Lindsay et al. (1975). The equations developed by Lindsay et al. (1975) were used in this report to model the effect of heat stress around joining on the number of lambs born and the number of ewes lambing.

Importantly, under Australian conditions the majority of breeding ewes and rams will experience repeated periods of heat stress during either mating, pregnancy and/or lactation, especially in those flocks mated during late spring/summer. It is, therefore, expected that the impacts of heat stress will be additive. In the extreme situation, in flocks which experience heat stress around mating and during pregnancy, the number of ewes which lamb and the number of lambs which are born will be substantially reduced, and the birthweight and survival of these lambs will also be reduced, potentially reducing weaning rates by 20 to 30%.

Using Australian Gridded Climate Data (AGCD) in conjunction with management data from 26 sheep producing regions across Australia and equations modified from Lindsay et al. (1975), we calculated the impacts of heat stress (number of days > 32 °C) during the mating period on ewe fertility. This was conducted both for the current climate, and a +1 °C or +3 °C increase in mean daily Australian temperature. For all mainland states, in flocks which joined from spring to early autumn (October to March), the incidence of heat stress (days over 32 °C) experienced under current climate conditions decreased the number of lambs born by 3 to 22% (mean: 9%). The reduction in numbers of lambs born due to heat stress is expected to rise to 4 to 23% (mean: 11%) and 5 to 24% (mean: 14%) should temperatures increase by 1 °C or 3°C, respectively. In flocks which are joined during late autumn/winter (April to September), the impacts of heat stress during the joining period were less severe, causing a 0 to 1% (mean: 0.3%), 0 to 2% (mean: 0.5%) and 0 to 3% (mean: 1.6%) decrease in lambs born under current, +1 °C and +3 °C conditions.

The impacts of heat stress during gestation on lamb birthweights and post-natal survival are difficult to quantify given the differences between experimental and field conditions. There is considerable variation in the frequency and duration of heat stress events experienced during the gestation of ewes joined between October and March. For flocks joined in October to March, days of moderate heat stress (THI > 75) account for 9 to 75% (mean: 45%) of the first 50 days of pregnancy, with this increasing to 14 to 82% (mean: 52%) and 26 to 97% (mean: 67%) should temperature increase by 1 °C or 3 °C, respectively. Of the sites studied, days of moderate heat stress accounted for < 5% of the middle third of pregnancy at 5 sites, with this reducing to 4 sites should temperature increase by 3 °C. However, for the remaining sites, moderate heat stress occurred on 9 to 67% (mean: 36%), 13 to 74 (mean: 43%) and 25 to 87% (mean: 59%) of days in the middle third of pregnancy (at current, +1 °C or +3 °C, respectively). Predictably, ewes mated during late autumn (April to September) experienced very few days of moderate heat stress during gestation under current or modelled conditions. However, days of mild heat stress (THI > 68) sufficient to reduce milk production of dairy sheep and cattle do occur throughout a reasonable proportion of lactation for spring lambing flocks. Specifically, for the current climate 33% and 58% of the first 50 and second 50 days of lactation had a THI > 68, with these values increasing to 38% and 62% should temperatures increase by 1 °C, and 49% and 72% if temperatures increase by 3 °C. Whether this heat stress translates to a reduction in milk production by meat and wool breeds of sheep is not known, but is worthy of future investigation.

In conclusion, based on an extensive review of the scientific literature and detailed analysis of the impacts of current and future climate on ewe fertility, it is clear that heat stress profoundly impairs the reproductive performance of the Australian flock. This impact is particularly significant for flocks which join during spring, summer and early autumn. Overall, based on the sites investigated, and their current seasonal joining patterns, it is estimated that 2.1 million potential lambs are lost due to heat stress under the current climate. In addition, heat stress during gestation is likely to retard conceptus development, particularly for flocks mated in spring/summer, with the potential to reduce lamb birthweights by 0.6 to 1.4 kg, and decrease survival to weaning by 20 to 30%. Should a +1 °C or +3 °C increase in temperatures occur, as is likely based on projections from climate models, the annual reduction in the number of lambs born will rise to 2.5 and 3.3 million, respectively. In conjunction, the severity of fetal growth retardation due to heat stress during gestation will increase, further decreasing the weaning rates of the Australian flock. Based on this review, it is clear that the profitability of the Australian sheep flock is extremely vulnerable to heat stress. It is therefore important to identify potential strategies to ameliorate and mitigate the risk associated with heat stress, and establish the economic costs of current and future heat stress for the Australian flock.

2. Knowledge Gaps

Based on our extensive literature review, there are a number of significant knowledge gaps which need to be filled if the true impacts of heat stress on fertility of the Australian sheep flock are to be fully understood, and if effective strategies to alleviate these impacts are to be developed.

2.1. Knowledge Gap 1. Field conditions; microclimates, heat stress and reproduction

Data describing the impacts of the climate experienced by pasture and rangeland sheep on their homeothermy, behaviour, resource use and reproduction are lacking. This applies to ewes at all stages of the breeding cycle (before joining through to weaning), as well as rams. More specifically, the following knowledge gaps have been identified:

- Under field conditions, the impact of high thermal load on the behaviour, resource use and physiology of ewes and rams is not known.

- The true impact of elevated THI on the various components which contribute to the weaning rate of the Australian flock, namely sexual behaviour, semen and oocyte quality, fertilisation, embryo survival, pregnancy rate, fetal development and lamb survival, remain unknown. This applies to both natural mating and artificial insemination.

- Most experiments and modelling exercises rely on temperature and humidity measured in a standard Stevenson screen at 1.2m. On a hot, calm day the envelope of air close to the ground that sheep occupy is likely to be much hotter than indicated using the Stevenson screen, especially in a dry paddock with limited evapo-transpiration. Most research on the micro-climates immediately surrounding livestock has been conducted in intensive conditions (e.g. cattle feedlots) or in confined conditions (e.g. during live sheep export). Understanding of the micro-climate experienced by sheep under field conditions is therefore limited, as is knowledge about variation in climate within paddocks (based on topography, wind movement, canopy cover and soil moisture). The ability of sheep to make use of these different microclimates to facilitate homeothermy is also unknown.

- The impact of heat stress during gestation on fetal development and programming (long-term effects on functional capacity) and subsequent progeny performance (growth, body composition, fertility, lactation potential and heat tolerance) is unknown.

- The Impact of heat stress during gestation and lactation on mammary development and milk production by Australian sheep breeds is not known.

- The ability of individuals to maintain a lower core temperature under high thermal loads remains to be properly established, as does the impact of this variation in homeothermy on fertility and reproduction. Fetal development and birthweight appear to be less impacted by maternal exposure to heat stress conditions in ewes which maintain lower core temperatures; however, whether this is true under field conditions is not known. Furthermore, the relationships between core temperature under high thermal load and mechanisms that determine fertility (i.e. ovarian function, oocyte quality, sperm numbers and quality, fertilisation rates, embryo survival, pregnancy maintenance and litter size) remain to be established.

- Understanding the phenotype and genotype of heat resilient sheep is poor, and it remains to be established whether heat resilience can be incorporated into breeding programs without compromising production traits.

- The physiological and endocrine mechanisms, as well as the stress activated pathways, that underlie reduced fertility and reproductive performance in heat stressed animals remain largely unknown.

2.2. Knowledge Gap 2. Ameliorating the negative effects of heat stress on sheep reproduction

A number of key knowledge gaps relating to ameliorating the impacts of heat stress through management of the sheep and its environment are discussed below.

- The opportunity to use nutrition to cost-effectively ameliorate the impacts of heat stress on the welfare, health and reproduction of sheep is not known. There is good evidence that temperature-induced reductions in feed intake are responsible for only a minor component of the observed reduction in conceptus development and birthweight. However, the impact of feed intake around mating, and during early pregnancy, on the fertility of heat stressed ewes and rams is not known.

- The potential to improve the fertility and fecundity of heat stressed sheep by reducing the heat increment of the feed offered, and optimising the energy and protein content is not known.

- The opportunity to use specific compounds and nutrients to facilitate homeothermy of sheep, and prevent the physiological, cellular and biological changes which occur in response to heat stress and impair fertility, health and welfare of sheep, remains largely unexplored.

- The benefits of modifying the microclimate experienced by sheep (i.e. shade, ground cover) and the availability of resources (feed, water) on their ability to maintain homeothermy, and the resultant impacts on reproduction, are largely unknown. It remains to be established whether the impacts of periods of heat stress can be negated or at least ameliorated, by modifying husbandry practices. These include changing shearing time to optimise wool cover, altering ewe:ram ratios, and joining for longer periods of time.

3. Priorities for future research to protect the Australian sheep flock from heat stress

It is evident that reproductive efficiency of the Australian sheep flock is severely impacted by heat stress. Current estimates indicate that high temperatures (> 32 °C) around mating reduce the number of lambs born by 6.5% on average across the sites investigated (median: 5%; range: 0 – 22%. When data from flocks which join between early spring and early autumn (October to March, inclusive) are considered, high temperatures around mating reduce the number of lambs born by 9.2% on average (median: 8%; range: 3 – 22%). It is also clear that the adverse impact of heat stress is likely to increase under projected future climatic conditions.

It is therefore imperative that the sheep industry develops strategies which ameliorate the impact of heat stress on reproductive efficiency. To be effective, it is essential that this program is underpinned by input and guidance from producers and producer bodies, with the research required likely to cover a large number of disciplines, including; reproductive physiology, nutrition, genetics, climatology, engineering, natural resource management and behaviour. Following discussion with the SALRC SA regional committee and a number of livestock consultants the following priority research areas and questions were developed.

3.1. Understanding the true impact of heat stress on reproduction of the Australian breeding flock

The main research questions which need to be addressed are:

3.1.1. What constitutes a thermal load sufficient to impair sheep reproduction?

Natural, cyclic patterns of temperature and humidity in the field differ from those imposed in the majority of climate-controlled studies. Temperature and humidity levels fluctuate during the day and night, with sheep exposed to differing patterns of heat stress conditions; acute (one or two days), intermittent (series of hot days interspersed with cooler day) and chronic (several days to weeks in succession). Furthermore, the impact of heat adaptation due to persistent exposure to heat stress conditions on ewe and ram fertility has not been established. Temperature regimes in the paddock are also likely to be a mosaic of microclimates created by differences in topography, wind flow, soil moisture and canopy cover, and differ to climate-controlled rooms and measurements taken at the nearest weather station. Based on this, we recommend that future research needs to be conducted in the following areas.

- Development of remote sensing technologies (such as internal temperature loggers and GPS devices) to observe, monitor and analyse the physiological, homeothermic and behavioural responses of individual sheep to the climate experienced between spring and early autumn, and to relate these responses to sexual behaviour and fertility measures. Further, this technology could be applied to longitudinal research to help determine if behavioural responses are repeatable over sequential years, and the extent to which these behavioural, physiological and homeothermic responses vary between individual animals.

- Quantification and mapping of microclimates to determine the extent and temporal stability of microclimates in field conditions and then to investigate how they are utilised by sheep. By monitoring the physical microclimate, the behaviour of individual sheep and the temperature of the sheep we can identify the direct effects of these microclimates on core body temperature and homeothermy. This research would help establish the relationship between various characteristics of the sheep (e.g. genetics, age, sex, pregnancy, lactation, body condition, wool cover and behavioural traits) and the level of heat stress to which they are exposed.

- Determine the responses of sheep to shade availability, (i.e. different types of shade including natural trees, artificial shelters, edible shrubs), and determine experimentally if there is a preference and benefit of providing shade of different types and different quantities. Analysing the costs and benefits of different shrubs and trees could involve a level of citizen science from landholders and partnerships with NRM bodies. The benefits of trees and shrubs extend beyond sources of shade for production and animal welfare. Some of the co-benefits include shelter for cold conditions, biodiversity and carbon sequestration. Therefore, the potential benefits of shade use for heat stress would further add to the benefits associated with the target of the sheep and beef industries to be Carbon Neutral by 2030 (CN30 initiative), as well as being of use to reduce lamb mortality during cold periods. The increased use of confinement feeding over summer presents further opportunities for natural and artificial shade.

- As explained in the review, the approach to climate modelling used here was to take a simple scaling approach. A more sophisticated and better resourced climate modelling exercise would utilise downscaled modelling to examine extreme temperatures and the humidity and wind expected with these extremes. Including changes to rainfall and evaporative demand would also enable modelling of pasture growth, which has important feedback for nutrition and energy balance as well as temperature close to the ground.

- Conduct controlled studies to determine the impact of acute, chronic and intermittent exposure to heat stress conditions on the components of ewe and ram fertility (i.e. sperm numbers and quality, oocyte quality, embryo survival, pregnancy rates, conceptus development, litter size and lamb survival). The heat stress conditions used in these controlled studies should match those experienced by sheep housed on pasture / rangelands. The impact of adaptations to heat stress due to prolonged exposure on fertility also require investigation as physiological adaptations to assist homeothermy may negatively impact reproductive processes. This research would make it possible to understand the physiological and biological impacts of heat stress on the reproductive axis, informing the development of effective amelioration strategies (i.e. nutrition, supplements).

3.1.2. What is the true impact of heat stress at key stages of the reproductive cycle on reproduction?

Based on our review, there are three knowledge gaps which need to be addressed; (1) understanding of the interaction between climate and reproduction within commercial flocks across Australia and for current genotypes; (2) understanding the impact of exposure to heat stress before, during or after pregnancy on performance of the resultant progeny; and (3) understanding the impacts of heat stress on milk production of Australian sheep breeds. Based on these gaps we recommend the following areas for research:

- The data available describing the impact of climate on sheep fertility in the field are based on studies conducted either 20 or 40 years ago. Therefore, the collection of up-to-date information for current genotypes and current breeds for effects of heat stress during periods of the reproductive cycle on ewe and ram fertility is required. This could be achieved in two ways; (1) using remote sensing technologies in ‘sentinel’ flocks (based on breed, climate and timing of mating) to determine the impact of natural variation in climate on reproductive outcomes; or (2) by using retrospective and prospective data from pre-identified production sites and producers, AI providers and pregnancy scanners and relating this to BoM climate date to establish critical THI thresholds (level and duration) above which reproductive outcomes (fertility, fetal growth, placental development, birthweight, litter size and weaning rate) are negatively impacted.

- The impact of heat stress on the phenotype of progeny born to heat-stressed ewes, and indeed heat-stressed rams, has not been investigated. Evidence that heat stress during gestation induces epigenetic and other persisting changes, and has the potential to impair growth and reproductive potential, is available from studies in cattle and pigs. It is also clear that heat stress *in utero* alters the heat tolerance of the progeny; however, results of studies in different species (cattle versus pigs) are contradictory as to whether progeny are more or less tolerant. Therefore, we recommend that research should be conducted to determine how heat stress during key periods of the reproductive cycle affects progeny performance.

- In dairy breeds of sheep and cattle, moderate elevations in THI reduce milk production, both directly in response to heat stress during lactation, and indirectly via impaired altering mammary development in response to heat stress during late gestation. We recommend that the impacts of elevated THI on milk production of Merino and other wool and meat sheep breeds commonly used in Australia be established, with a view to developing mitigation strategies.

3.2. Developing amelioration strategies to reduce the impacts of heat stress on ewe and ram reproduction rates

Strategies need to be developed which can be implemented by producers to ameliorate the impact of heat stress and to protect the national flock from the negative impacts of heat stress. Whilst the development of these strategies can be informed by **Section 3.1**, a number of suggestions have been developed in conjunction with feedback from producers and industry consultants (See Stephen Lee's report). These suggestions have been divided into five sections, detailed below, with each section or amelioration strategy deemed to be of equal importance. Combinations of each type of strategy will likely be effective at reducing the risk of heat stress induced losses in reproductive output.

3.2.1. Nutritional strategies to ameliorate the impacts of heat stress

Modifying ewe and ram nutrition during periods of heat stress is a strategy that can readily be adopted by producers, assuming it is cost effective (economic impacts described in **Section 5**). A majority of producers have some infrastructure for supplementary feeding, which combined with the wider adoption of self-regulating feeders and water dispensers, make it a relatively simple process to adopt nutrient strategies that reduce the impact of heat stress. Similar to shade use, the increased use of confinement feeding over summer presents further opportunities to fine-tune feeding of sheep to minimise the impacts of heat stress during key periods of the reproductive cycle. Therefore, research is required to identify cost-effective nutritional supplements or compounds that ameliorate the impacts of heat stress on reproduction and, indeed on health and welfare of the animal.

Based on the outcomes of the review, focus should be on supplements and nutrients that will achieve the following outcomes when sheep are exposed to thermal stress:

- Prevent heat induced suppression of gonadotrophin release and, thus maintain correct endocrine support for reproductive processes
- Protect the oocyte, embryo and the progesterone-producing corpora lutea from heat stress, thus promoting embryo survival, facilitating implantation and ensuring pregnancy is maintained to term
- Protect the testis and sperm from heat induced damage, thus maintaining production of high-quality sperm and ensuring fertilisation
- Mitigate the negative impacts of heat stress on placental and fetal development, thus maintaining birthweights and optimising lamb survival and performance.

Research should also be conducted to identify, develop and utilise compounds or nutrients which facilitate homeothermy (reducing the direct impacts of elevated core temperature on reproductive function), and maintain feed intake and digestive health when sheep are exposed to heat stress.

Another area worthy of investigation is whether simple modification of the diets to optimise the energy, amino acid and fibre content of sheep diets during summer will reduce the heat increment associated with digestion sufficiently that feed intake is maintained. Alternatively, modifying the composition of the diet such that any reductions in feed intake can be compensated for by the nutritional content of the diet is also worth investigating.

Supplementary feeding can be expensive when used under extensive grazing conditions. Further development of robust feeding/nutrient dispensing systems is required so that regulation and fine-tuning of the amounts of nutrients supplied at the most effective times for ameliorating heat stress should be a priority. An understanding of the changes in rumen digestive function while transitioning between paddock and supplementary feed types would form an integral part of such a research program.

3.2.2. Use of shade to ameliorate the impacts of heat stress

Lack of shade for sheep during the summer is a prime ethical issue apart from the negative effects, it may have on reproductive function and productive output of sheep. There is a myriad of options available for research but it is the principles that need to be developed so that the provision of shade, paddock feed (potentially supplementary feed), and water are optimised for homeostasis and reproductive capacity.

Trees, shrubs or artificial structures are alternatives to provide shade in the paddock. There are many options to be contemplated but issues such as plant species, the longevity and cost of establishment and maintenance are important considerations to be researched.

3.2.3. Modifying mating protocols to account for impacts of heat stress

Mating of most sheep in Australia occurs at a time when many ewes are in anoestrus in the early spring and summer months (November and December) and are transitioning to the breeding season in the late summer period (February onwards). Current practices have rams with the ewes for at least five weeks to cover two oestrous cycles. Teaser rams may be introduced to the flock prior to the mating period to maximise the number of cycles that occur during this period. If significant heat stress occurs during the first 2-3 weeks of the mating period, then depending on the fertility of the rams, those ewes that suffer embryonic loss or fertilisation failure have an opportunity to return to service in the following 2-3 weeks. However, if the ewes and rams experience a significant heat load throughout the mating period, a substantial reduction in pregnancy rates would be expected. Changing to mating protocols, such as extending the mating period, increasing the number of rams per ewe or introducing fresh rams maintained in cooler conditions, are possible options worthy of investigation. A simple alternative for graziers is to pregnancy test flocks mated during the summer and then re-mate non-pregnant ewes but there is an economic cost associated with the supply of smaller offspring at times of peak market demand.

3.2.4. Containment mating as a strategy to alleviate heat stress

Mating of sheep under intensive conditions may provide some advantages for reducing the effects of heat stress on reproductive function, such as easier supply of shade and appropriate nutrients, application of water to the skin as well as the pen surface, reduced need for animal movement to obtain food, and potential for greater air movement. The scenario of containment mating, and its opportunity to test various heat amelioration strategies, is an opportunity to gain valuable information for both intensive and extensive systems of production. In a similar manner, even though mating may occur in the open field, rams could be kept in containment prior to mating to minimise the effects of heat stress on ram fertility.

3.2.5. Modifying time of shearing

The fleece provides some protection against heat stress by reducing radiant heat gain by maintaining a moist micro-environment on the surface of the skin. Whilst shearing may reduce respiration rate and increase the animal’s capacity to thermo-regulate there is likely to be an optimal thickness of fleece that, on one hand, avoids the likelihood of sunburn but, on the other hand, provides protection against heat stress. However, the optimum time for shearing prior to mating is yet to be established.

3.3. Identification, characterisation and selection of heat resilient ewes and rams

As discussed in the review, preliminary evidence suggests that ewes differ in their ability to maintain their core temperature in the face of heat stress and that rams also differ in their ability to maintain scrotal temperature when exposed to heat stress. It is recommended that research be conducted to identify and measure parameters of homeothermy, and to determine their repeatability within individuals, as well as between flocks and breeds. Improved knowledge of the physiology of sheep with differing ability to maintain homeothermy under conditions of heat stress is a vital first step towards selection for improved heat tolerance. Quantitative genetic selection could be possible if the parameters determining heat tolerance are heritable. This approach is highly likely to succeed, based on work in cattle which demonstrates the potential to identify the molecular mechanisms responsible for heat stress, and that opportunities do exist to improve thermo-tolerance through marker-assisted selection.

4. Outcomes of consultation meeting with SALRC SA regional committee and consultants

4.1. Consultation format

On the 13th December 2019, the SALRC SA regional committee along with livestock consultants, livestock scientists and people with experience in policy development and natural resource management contributed to the consultation. People involved in consultation: Jane Kellock, Allan Piggott, Troy Fischer, Paul Smith, Elke Hocking, Bruce Creek, Taryn Mangelsdorf, Wayne Pitchford, Michael Blake, Andrew Curtis, as well as 7 members of the project team (Dr's van Wettere, Simon Walker, Dave Kleemann, Alice Weaver, Peter Hayman, Jen Kelly and Alyce Swinbourne). All participants were provided with the pre-reading (milestone report 1) which included detailed descriptions of current and predicted effects of heat on sheep reproduction. In addition, there was a brief presentation on the project terms of reference, methods used, and results. This provided the basis for discussion on:

- Existing mitigation options and their relevance/suitability for Australian sheep production systems
- Knowledge gaps including scope for accessing other existing records to fill gaps
- Areas where further research is required

4.2. Initial feedback

All participating in the consultation session provided general feedback on the exceptional thoroughness of the report and the very substantial impacts of heat on reproduction in sheep, even for the current climate. There was a sense of urgency in:

- Providing insights to producers on the potential impacts of heat on sheep reproduction
- Identifying and implementing existing mitigation strategies on-farm

- Initiating research in areas where knowledge is seen to be lacking

4.3. Consideration of existing mitigation options

Shade and double mating were identified as existing mitigation options which appear potentially well suited to (further) implementation in sheep production systems. In contrast, feedback was received that most producers would likely be reluctant to shift time of mating, even if existing time of mating was not optimally aligned with the feed curve.

Provision of shade was considered in two separate production circumstances; containment zones and extensive grazing. Containment zones are rapidly becoming part of many sheep production systems, primarily in response to drought or regular periods of restricted feed availability. Provision of shade and/or sprinklers in containment zones was viewed as achievable. In extensive grazing systems, the provision of shade through existing plans or targeted planting was viewed as an obvious potential mitigation strategy. This would have further benefits beyond mitigation of heat stress linked with land stewardship and the red meat industry’s CN30 target.

Double mating: the participants indicated the practice of double mating is quite common and had the advantage of reducing joining periods, with resultant ability to better manage critical periods for ewe and lamb during gestation and early development respectively. A question remains on how effective double mating would be in reducing impacts of heat stress on reproduction (ram and ewes) and how it compares economically with better aligning feed availability and feed requirements. Suggested formats for double mating include:

- Mating twice a year or every 8 months
- Mating early summer and again 2 months later in later summer (noting confounding impact of nutrition at different times)

4.4. Research and development of further mitigation options

Several areas of importance relating to mitigation options were identified and considered at the workshop. The primary area of interest was nutrition and supplementation. Feedback from producers on the potential to develop targeted nutritional or hormonal supplementation to reduce the impacts of heat stress was viewed as a high priority. In part, this was linked with consideration that such strategies could be readily implemented alongside existing practice. Key needs were minimal additional handling, complexity or cost. It was noted that many producers supplementary feed over summer, and thus provision of additional inputs/supplement would be relatively easy to achieve.

4.5. Further considerations of additional research, development and mitigation of heat stress impacts on sheep reproduction

- Historic records: there may be potential to access existing commercial data from artificial insemination and embryo transfers to assess relationship to weather records prior to, and during, gestation.
- Containment areas: heat stress studies potentially more ‘testable’ in containment areas
- Further work should primarily focus on Merino sheep as they are predominantly in heat stress climates
- Fewer rams, so adoption pathways may be easier in this space compared to ewes.

4.6. Areas of limited knowledge that were viewed as important by workshop participants

- Possibly more important; during a heatwave how cool do the nights get after a hot day?
- Are rams and ram performance more sensitive to heat than ewes? i.e. do cooler nights allow the ewe to cope but the impact on rams has already occurred?
- Management options to capitalise on microclimates created by shade and/or landscape
    - Need to monitor animals to get a microclimate understanding
        - Close to the ground could be incredibly hot on a hot day
        - Are there cool patches in paddocks, and do the sheep find these cool patches?
        - If the shade is limited, do sheep group together and do they actually generate a higher microclimate THI?
    - What is the difference between THI based on measurement in Stevenson screen at 1.2m and the envelope of air surrounding the sheep? On a calm day in a dry paddock will the sheep will be hotter?
- How well do historical studies correlate with current genetics?
- Insights from goats
    - Why do they seem to handle heat stress better than sheep?
    - Browsing animals and seasonal animals; are they better at seeking out microclimates?
    - What are the differences in physiology?
- Are there any advantages/considerations in mitigating heat stress through wool length? Would shearing every 6 months assist this?
- Genetics? Selecting for better heat tolerance
    - Is there something like the slick gene in cattle?

- Can we identify trait/s to select on? e.g. more capillaries closer to skin surface? How do we identify the traits?
- Likely to be adaptations BUT will they impair other traits such as fertility traits
- Identify individuals with different thermotolerance and see what differs genetically
- Timing of selection relative to maturity needs to be considered

5. The economic impacts of heat stress on the Australian sheep flock

Based on observed and projected increases in temperature exposure of the Australian sheep flock, thermal stress will occur more frequently and for longer periods. This will adversely affect the national flock because thermal environment is the largest single stressor affecting the development, growth and reproduction of sheep. This analysis is part of a larger project, the first milestone of which was a review of the literature on the effect of heat stress on reproduction. The important findings were:

- Heat stress during the mating period adversely affects ewe fertility
- The impacts of heat stress on ewes are most severe when experienced from five days before until five days after oestrus
- The number of ewes lambing and the number of lambs born per 100 ewes joined were negatively correlated with the number of days per week during the mating period when ambient temperatures were ≥ 32.2 °C
- Increased heat load reduces semen quality. In contrast with ewes, these effects are delayed being observed between 9 and 60 days after heating
- Heat stress for prolonged periods during pregnancy reduces lamb birthweight, decreases the proportion of lambs born alive by 30% and causes approximately 25% more lambs to die after birth
- Heat stress during pregnancy also impairs the growth, reproductive potential, milk production and thermoregulation of offspring, and even moderate increases in heat load during lactation reduce milk production.

Stage 1 of this review focussed on quantifying the impact of heat stress on reproductive productivity per ewe. Consider of the impact of climate change on pasture growth and availability, which could be large, was not included in that review. Thamo et al. (2017) examined the impacts of altering crop and pasture productivity for a range of future scenarios and found that per hectare livestock production was severely affected in realistic climate change scenarios.

> "*Although severe climate change reduces the productivity of both crops and pasture, the relative reductions in the production of animal-derived outputs are disproportionately large*" (Thamo et al., 2017)

Therefore, the following analysis had three components that focused on quantifying:

1) The economic cost of heat stress. This is a comparison of the profitability without heat stress against the current and projected levels of heat stress with the same animals and same pasture production. The analysis was carried out:
    a) using only the production effects for which there is a reasonable degree of certainty (the impact of heat stress on reproduction)
    b) using other production effects that have not been well quantified in previous research (including the impact of heat stress on birth weight and survival)

2) The potential value of amelioration strategies that can be implemented. This component of the analysis evaluated a range of strategies that farmers could implement to reduce the impacts of heat stress and claw back some of the cost quantified in step **Error! Reference source not found.**. The focus for this section was on strategies that are amenable to research within the context of the MLA R & D budget.

3) The RD&E budget that is justified if the potential amelioration strategies could be developed and adopted in the Australian sheep industry

The calculations in this report are based on estimates made about the impact of heat stress on reproduction and lamb production reported in Stage 1 of this review.

5.1. Analysis and results

The economic analysis quantified both the expected reduction in profit if no amelioration strategies were implemented and the improvement in profit from this baseline if amelioration strategies were implemented.

The data for each region used in this analysis is presented in **Appendix 1**: Production assumptions

Table 0-1: Current production levels and impact of heat stress on EL-number of ewe lambing (‘000 hd), LB-number of lambs born (‘000 hd) and BW-birth weight (%) for the 3 climate scenarios (current, +1 °C, +3 °C). Source: van Wettere et al. (2019) Table 3-3 and 3-4.

			Current production		Climate Scenario (production impact compared with ‘no heat stress’)								
					Current			+1°C			+3°C		
State	Site	Joining	Ewes (‘000)	Lambs marked (‘000)	EL (‘000)	LB (‘000)	BW (%)	EL (‘000)	LB (‘000)	BW (%)	EL (‘000)	LB (‘000)	BW (%)
QLD	Longreach	Mar	54.6	30.9	-9.2	-12.0	0	-9.8	-12.8	0	-10.1	-13.2	0
	Cunnamulla	Mar	44.7	22.2	-5.6	-7.2	0	-6.3	-8.2	0	-7.2	-9.4	0
	St George	May	154.6	138.8	0	0	0	-0.1	-0.2	0	-1.1	-1.5	0
NSW	Wilcannia	Feb	288.2	242.3	-38.1	-49.4	0	-41.6	-54.0	0	-46.8	-60.7	-15.0%
	Gunnedah	Apr	31.9	33.8	-0.1	-0.1	0	-0.2	-0.2	0	-0.8	-1	0
	Armidale	Apr	298.7	278.2	0	0	0	0	0	0	-0.1	-0.2	0

	Trangie	May	149.1	144.5	0	0	0	0	0	0	-0.2	-0.2	0
	Dubbo	Mar	401.8	410.7	-18.8	-24.3	0	-25.1	-32.5	0	-42.9	-55.6	0
	Griffith	Dec	20.7	20.1	-1.5	-1.9	-17.5%	-1.7	-2.2	-17.5%	-2.3	-2.9	-17.5%
	West Wyalong	Dec	283.1	269.7	-20.2	-26.1	-17.5%	-24.4	-31.6	-17.5%	-32.3	-41.9	-17.5%
	Young	Mar	800.7	802.9	-24.9	-32.3	0	-34.1	-44.2	0	-61.6	-79.8	0
VIC	Walpeup	Apr	84.1	86.5	-0.4	-0.6	0	-0.7	-0.9	0	-1.8	-2.4	0
	Bendigo	Mar	108.5	100.1	-2.1	-2.7	0	-2.9	-3.8	0	-5.5	-7.2	0
	Shepparton	Dec	58.7	64.1	-2.0	-2.6	-17.5%	-2.6	-3.4	-17.5%	-4.1	-5.4	-17.5%
	Hamilton	Apr	1 068.5	1069.5	-1.1	-1.4	0	-2.0	-2.6	0	-7.4	-9.5	0
	Ballarat	May	37.5	40.7	-0.3	-0.4	0	-0.5	-0.6	0	-1.0	-1.2	0
SA	Minnipa	Dec	70.9	64.5	-4.1	-5.3	-17.5%	-5.0	-6.4	-17.5%	-6.4	-8.3	-17.5%
	Rosedale	Dec	41.7	39.3	-1.8	-2.4	-17.5%	-2.2	-2.8	-17.5%	-2.8	-3.7	-17.5%
	Renmark	Feb	96.4	92.7	-8.9	-11.5	0	-9.9	-12.9	0	-12.0	-15.5	0
	Struan	Dec	502.7	552.3	-12.3	-15.9	-12.5%	-15.4	-19.9	-17.5%	-22.5	-29.2	-17.5%
WA	Geraldton	Feb	79.7	66.3	-6.5	-8.5	-12.5%	-7.2	-9.3	-12.5%	-9.1	-11.9	-20.0%
	Northam	Feb	75.4	70.1	-8.6	-11.1	-12.5%	-9.7	-12.6	-12.5%	-11.8	-15.3	-20.0%
	Katanning	Feb	103.4	94.6	-5.4	-7.0	-12.5%	-6.7	-8.6	-12.5%	-9.8	-12.7	-20.0%
	Esperance	Feb	302.7	276.1	-7.5	-9.7	0	-8.7	-11.3	0	-12.2	-15.8	0
TAS	Launceston	Apr	19.7	22.1	0	0	0	0	0	0	0	0	0
	Hobart	May	1.1	0.343	0	0	0	0	0	0	0	0	0

Appendix 2: MIDAS lamb values used

Table 0-1: Value of an extra lamb. Derived from Young et al., 2014. MIDAS modelling for SW Victoria.

	Lamb price ($/kg DW)						
	$2	$3	$4	$5	$6	$7	$8
Merino[1]	15	27	39	52	65	78	91
Merino-Terminal[1]	24	43	56	74	100	111	129.5
Maternal[1]	20	43	54	70	87	105	122.5

[1] These values are the values for an extra lamb weaned if that lamb was achieved from a combination of increased conception (fertility and fecundity) and increased survival.

Colour coding:

Values published in Young *et al.* 2014.
Extrapolated from the value at $5/kg, using 25% per $1/kg

, and includes:

1) Number of ewes mated
2) Number of lambs marked
3) Impact of each heat stress scenario on:
    a) number of ewes lambing
    b) number of lambs born
    c) lamb birth weight

Analysis from the MIDAS whole-farm model (**Appendix 2**: MIDAS lamb values used) was used to quantify the value of varying the number of lambs weaned due to pregnancy rates and lamb survival rates (Young *et al.* 2014). That analysis included the costs associated with feeding the extra ewes that were pregnant and lactating, and feeding the extra progeny through to when they are sold or integrated into the flock as breeding ewes. It also accounted for the difference in production of single and twin lambs and the different level of production of dry, single and twin bearing ewes. Young *et al.* (2014) only considered lamb price in the range $2 to $6/Kg DW. For this analysis, it was extended out to $8/Kg. The values used in this analysis are reproduced in (**Appendix 2**: MIDAS lamb values used)

The standard discount rate used in the analysis was 5%.

5.2. Price levels

The standard prices used in the analysis were:

Table 0-1: Prices used in the analysis and the sensitivity rage examined.

Parameter	Description	Units	Std price	Sensitivity range
Meat:	Finished lamb	$/Kg DW	$6	± $3/Kg
	CFA ewes	$/hd	$120	± 50%
Wool	20μ fleece	$/Kg clean	$20	
Supplementary feed[1]	Concentrate	c/MJ of ME[2]	3.0	

Roughage	c/MJ of ME	3.0

[1] See **Appendix 4** for source of values.

[2] Cost per MJ purchased

Sensitivity analysis was carried out on the price of meat as a complex (i.e. all meat prices were varied together). For simplicity of reporting, the lamb price is used as the indicator price for both the lamb price and ewe price changes. Sensitivity analysis was not carried out on wool price because the results of Young *et al.* (2014) showed that the value of an extra lamb surviving was not sensitive to the price of wool.

5.3. Cost of heat stress

The first component of the analysis was calculated from the expected reduction in number of lambs weaned associated with the increased frequency of heat stress events that was quantified for 26 sheep producing regions across Australia. This was combined with the value of an extra lamb surviving to weaning. This analysis provides a snapshot of the aggregated industry reduction in profit per farm and the projected impact on number of lambs weaned and the cost per ewe.

Two levels of economic impact were estimated:

1) Robust model, based solely on the effect of heat stress on the reduction in lambs born and ewes lambing per joined ewe for both current, +1 °C and + 3°C temperature scenarios. The assumptions behind these production effects are robust, being based on two large scale farm trials that developed relationships between temperature during the joining period and reduction in the number of lambs born.
2) Best bet model, as for the robust model, but included the cost of reduced lamb birthweight due to heat stress. The assumptions underpinning this part of the analysis are less certain being based on small-scale heat chamber experiments that did not generate quantitative relationships between the level of heat stress and the reduction in productivity, but did show that persistent heat stress during mid pregnancy will reduce birthweight by 10 to 20%.

The distribution of joining date for each location was based on breeding management calendars developed for each site using data extrapolated from Croker et al. (2009) as well as information provided by regional livestock consultants, industry partners and commercial producers (details regarding site selection and breeding management calendars were described in Stage 1 of this review). From this information, the median joining date was calculated and the impact of heat stress based on this joining date was calculated or estimated (**Appendix 6**: Impacts of heat stress on number of lambs weaned calculated for each region and each climate scenario..

The estimated impact of heat stress on reproduction in each region within States was scaled to a State level based on the number of ewes in the regions evaluated and the number of ewes in the State (**Table** 0-2). Summing these scaled values generates an estimate for a national ewe flock of 33.3 million ewes.

Table 0-2: Ewe numbers in each state and the scalar calculated to expand the analysis to a national level.

State	# of ewe in state (‘000 hd)	# of ewes in regions evaluated (‘000 hd)	Scalar (applied to each region in that state)
QLD	878.3	253.9	3.46
NSW	11 947.5	2 274.2	5.25
VIC	6 748.1	1 357.3	4.97
SA	5 455.3	711.7	7.67
WA	7 199.9	561.2	12.83
TAS	1 129.5	20.8	54.30
Total	33 359.6		

The number of lambs born and lambs weaned was estimated for a scenario in which the ewes were not subject to heat stress. This ‘no stress’ level became the baseline from which the reduction in lambs weaned was calculated. The ‘no stress’ lambs-born was calculated from the estimate of the current number of lambs marked, the estimated lamb survival to marking and the estimate of the reduction in the number of lambs born with the current level of heat stress.

$$lambs\ born\ (no\ stress) = \frac{current\ lambs\ marked}{survival\ to\ marking} + current\ loss\ of\ lambs\ born$$

The reduction in the number of lambs weaned was calculated as the difference between the ‘no stress’ number of lambs weaned

$$(no\ stress\ lambs\ born * survival\ to\ weaning)$$

and the number of lambs weaned with heat stress

$$(no\ stress\ lamb\ born - reduction\ lambs\ born) * (\ survival\ to\ weaning - reduction\ survival)$$

The reduction in survival was calculated from the estimated reduction in birthweight (**Appendix 1**: Production assumptions and the relationship between birthweight and survival (Oldham et al. (2011); **Appendix 3**: Calculating survival from birthweight

Table 0-3 is the calculated reduction in survival using the parameters from **Table** 0-4.

Table 0-3: Effect of change in birthweight on lamb survival from birth to weaning.

Birthweight	Survival to weaning
-12.5%	-5.6%
-15%	-7.2%
-17.5%	-9.1%
-20%	-11.1%

Table 0-4: Parameters used to calculate the impact of birthweight reduction on survival reduction.

Parameter		Value
Estimated survival		
	birth to marking	76%
	birth to weaning	75%
Proportion of twins		33%
Average birthweight		5.3Kg
Birthweight reduction of twins		1.1Kg

The analysis has been done with a specific number of ewes in each region and a specific number of ewes in the national flock. This is making an implicit assumption that farmers have not changed enterprise scale as an option to ameliorate the effects of heat stress. This implicit assumption is also made in other analyses that evaluate national impacts of production changes (Sackett et al., 2006; Young et al., 2014)

The analysis also does not include the costs associated with reduced production of progeny from heat stressed ewes, including the epigenetic effects and impacts on growth rate before and after weaning, as well as post-weaning survival. Omitting these effects is due to lack of data with which to make estimates or conflicting evidence in the literature.

The current national cost of heat stress is estimated to be $97 million annually for the robust model or $168 million for the best bet model (lamb price $6/Kg). This increases up to $166 million or $278 million annually in a climate scenario +3 °C (**Table** 0-5 and
Table 0-6).

The national cost of heat stress is sensitive to the price of meat. The best bet estimate for the current climate scenario varies from $75m/yr up to $228m/yr at $8/Kg for lamb. These reductions in profit are associated with an annual reduction in the number of lambs weaned of 2.0 million currently increasing to 3.3 million lambs in the +3 °C scenario (
Table 0-7).

The reduction in profit per ewe in the national flock due to heat stress averages $2.91 for the robust model and $5.04 for the best bet model (lamb $6/Kg, current climate). This is an indication of the amount that could be spent per ewe to ameliorate heat stress. However, the value varies from $0 up to $15.50 per head in the individual regions (**Figure** 0-1 and **Table** 0-8).

This range is more informative and in regions that are most impacted by heat stress the impact per ewe could be up to $23.70 if the +3 °C scenario becomes reality.

Table 0-5: Robust model (confident assumptions) for the total national cost and average cost per ewe of the reduction in the value of lambs weaned for each climate scenario and a range of meat price scenarios.

Climate scenario	Current		+1 °C		+3 °C	
Lamb price	$m	$/ewe	$m	$/ewe	$m	$/ewe
$3/Kg	43	1.30	52	1.56	74	2.21
$4/Kg	57	1.72	69	2.06	98	2.93
$5/Kg	75	2.26	91	2.71	129	3.85
$6/Kg	97	2.91	117	3.50	166	4.97
$7/Kg	113	3.39	136	4.07	193	5.78
$8/Kg	132	3.95	158	4.75	225	6.75

Table 0-6: Best bet model (all assumptions) for the total national cost and average cost per ewe of the reduction in the value of lambs weaned for each climate scenario and a range of meat price scenarios

Climate scenario	Current		+1 °C		+3 °C	
Lamb price	$m	$/ewe	$m	$/ewe	$m	$/ewe
$3/Kg	75	2.50	91	2.72	124	3.71
$4/Kg	99	2.97	120	3.59	164	4.91
$5/Kg	130	3.91	158	4.73	216	6.46
$6/Kg	168	5.04	203	6.09	278	8.33
$7/Kg	196	5.86	237	7.09	323	9.70
$8/Kg	228	6.84	276	8.28	377	11.31

Table 0-7: National level reduction in lambs weaned per year and average reduction in lambs weaned per ewe joined for the robust model and the best bet model.

	Current		+1 °C		+3 °C	
Model	‘000 head	Lambs weaned (%)	‘000 head	Lambs weaned (%)	‘000 head	Lambs weaned (%)
Robust	1158	-3.5	1391	-4.2	1975	-5.9
Best bet	2003	-6.0	2423	-7.3	3312	-9.9

Error! Reference source not found. plots the marginal cost of heat stress per ewe against the scaled number of ewes impacted. The area under the curve is the cost of heat stress incurred by the industry; 40% of the flock has a cost of $1/ewe or less and 40% of the flock have a cost of $10/ewe or more. These regions above $10/ewe incur the majority of the national cost. In these regions an amelioration strategy that halves the cost of heat stress will still be profitable if the cost to implement the strategy is $5/ewe.

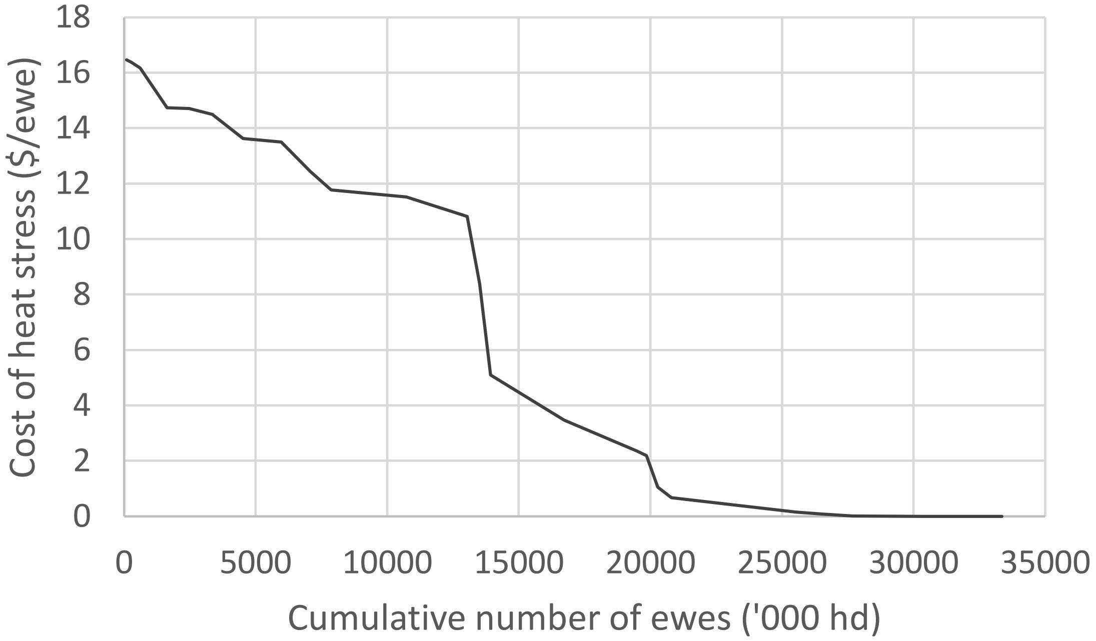

Figure 0-1. Distribution of the cost of heat stress ($/ewe) across the national flock. Best bet model, +1 °C scenario with lamb $6/Kg.

5.4. Value of Amelioration Strategies

The second component of the analysis was a preliminary examination of the value that could be achieved from on-farm amelioration strategies which could be implemented to reduce the impact of heat stress on reproduction. The focus was on the potential cost of the amelioration and the proportion of the impact of heat stress that might be ameliorated. Therefore, this analysis was focused on strategies that could be developed through research and development (

Table 0-9).

Table 0-8 Total reduction in profit due to heat stress (per ewe) in each region for the standard price scenario (lamb $6/kg).

	Analysis scenario					
	Robust model (confident assumptions)			Best bet model (all assumptions)		
State Site	Current	+1 °C	+3 °C	Current	+1 °C	+3 °C
QLD						
Longreach	754 (13.8)	803 (14.7)	827 (15.1)	754 (13.8)	803 (14.7)	827 (15.1)
Cunnamulla	454 (10.1)	515 (11.5)	589 (13.2)	454 (10.1)	515 (11.5)	589 (13.2)
St George	2 (0.0)	12 (0.1)	93 (0.6)	2 (0.0)	12 (0.1)	93 (0.6)
NSW						
Wilcannia	3108 (10.8)	3394 (11.8)	3818 (13.2)	3108 (10.8)	3394 (11.8)	5690 (19.7)
Gunnedah	5 (0.2)	13 (0.4)	64 (2.0)	5 (0.2)	13 (0.4)	64 (2.0)
Armidale			12 (0.0)			12 (0.0)
Trangie		1 (0.0)	14 (0.1)		1 (0.0)	14 (0.1)
Dubbo	1530 (3.8)	2047 (5.1)	3499 (8.7)	1530 (3.8)	2047 (5.1)	3499 (8.7)
Griffith	119 (5.8)	139 (6.7)	185 (9.0)	322 (15.5)	339 (16.4)	380 (18.3)
West Wyalong	1643 (5.8)	1988 (7.0)	2634 (9.3)	4358 (15.4)	4661 (16.5)	5229 (18.5)
Young	2030 (2.5)	2780 (3.5)	5020 (6.3)	2030 (2.5)	2780 (3.5)	5020 (6.3)
VIC						
Walpeup	36 (0.4)	57 (0.7)	151 (1.8)	36 (0.4)	57 (0.7)	151 (1.8)
Bendigo	172 (1.6)	237 (2.2)	451 (4.2)	172 (1.6)	237 (2.2)	451 (4.2)
Shepparton	164 (2.8)	211 (3.6)	338 (5.8)	809 (13.8)	851 (14.5)	962 (16.4)
Hamilton	86 (0.1)	161 (0.2)	600 (0.6)	86 (0.1)	161 (0.2)	600 (0.6)
Ballarat	25 (0.7)	40 (1.1)	78 (2.1)	25 (0.7)	40 (1.1)	78 (2.1)
SA						
Minnipa	335 (4.7)	404 (5.7)	523 (7.4)	984 (13.9)	1045 (14.7)	1150 (16.2)
Rosedale	148 (3.5)	176 (4.2)	232 (5.6)	543 (13.0)	568 (13.6)	618 (14.8)
Renmark	725 (7.5)	808 (8.4)	975 (10.1)	725 (7.5)	808 (8.4)	975 (10.1)
Struan	1003 (2.0)	1255 (2.5)	1838 (3.7)	4405 (8.8)	6784 (13.5)	7296 (14.5)
WA						
Geraldton	533 (6.7)	586 (7.4)	746 (9.4)	941 (11.8)	991 (12.4)	1531 (19.2)
Northam	699 (9.3)	794 (10.5)	963 (12.8)	1131 (15.0)	1219 (16.2)	1788 (23.7)
Katanning	439 (4.2)	544 (5.3)	801 (7.7)	1021 (9.9)	1119 (10.8)	1914 (18.5)
Esperance	609 (2.0)	711 (2.4)	991 (3.3)	609 (2.0)	711 (2.4)	991 (3.3)

Note: to generate the value for the national flock each region is scaled based on the number of ewes in each state compared with the regions evaluated in that state.

Table 0-9: Strategies evaluated to ameliorate the impacts of heat stress on reproduction.

Strategy	Detail
Shelter	Trees, shrubs, artificial shelter
Nutrition	Increasing diet quality
Containment mating	Intensive control of the mating environment
Mating protocol	Mate for an extra cycle
Time of shearing	
Time of Lambing	Delay lambing to spring/summer
Genetic selection	Add heat tolerance to the breeding objective

5.4.1.Trees, shrubs & artificial shelter

Shelter has the potential to reduce the stress experienced by the animals by reducing the energy absorbed from the sun. The efficacy of shelter in broadacre situations depends on the shade seeking behaviour of the animals, which is likely to be impacted by the grazing conditions. Furthermore, the density of the animals in the shade may affect air flow which may reduce cooling associated with evaporation. These behaviours may be difficult to influence in a broadacre situation reducing the likelihood that research can deliver a practical outcome. Therefore, research should be carried out into understanding and managing the shade seeking behaviour of the animals to maximise the utilisation of shade provided. Additionally, the level of shade on broadacre farms has not be quantified; however, this is a necessary parameter in order to calculate the industry benefit of providing extra shade.

Trees

Shelter from trees can be provided in a previously bare paddock in an agroforestry format. The cost incurred will be dependent on the income produced from the timber (or oil in the case of oil mallees) compared to the grazing foregone due to the area occupied by the trees and the reduction in pasture productivity due to competition for water, light and nutrients. Research into improving the profitability of agroforestry is outside the scope of the MLA research budget and will not be evaluated in the context of provision of shade. However, for properties that currently have tree cover, there will be limited benefit from provision of extra shade.

Shrubs

Improving the profitability of shrubs for shade is predominantly associated with improving the grazing value that can be achieved and as such is a feedbase issue. However, the added benefit of the shade provided by the shrubs would complement profitability.

Artificial shelter

In a broadacre scenario, the cost of providing artificial shade depends on the area of shelter required per animal and the effective utilisation of the shade. For this analysis the cost of shade cloth was examined assuming that it could be erected in a ‘shade sail’ arrangement to minimise the cost associated with framing. The cost of reduced pasture growth due to blocking sunlight is not included in the analysis because the animals would be camping in the paddock in some location and the production in the sheep camp areas is usually low because of overgrazing.

Table 0-10: Assumptions related to cost of providing artificial shade

		Unit	Assumption
Sail area		m^2	100
Component costs			
	Shade cloth	$\$/m^2$	\$2.70[1]
	Wire rope	\$/m	\$0.30[2]
	Reinforcing and stitching	\$/sail	\$100
Labour			
	Construction	hr/sail	3
	Maintenance	hr/sail	1
	Cost	\$/hr	50
Lifespan			15 yrs

[1] Bunnings 5m roll 3.66m \$50 70% UV block

[2] Alibaba 500m roll of 8mm stainless steel cable.

The annual cost of providing artificial shelter based on the above assumptions is $\$1/m^2$. In an extensive grazing situation, the area of shade required depends on animal behaviour and the density at which the animals camp under the shade. Assuming the area required per ewe is 1 m^2 this equates to \$1/ewe. The level of amelioration achieved depends on the animals utilising the shade and the importance of solar radiation to heat stress. The benefit may be in the range 0 to 50%. Further research is required to demonstrate the benefits and application in a broadacre situation and improve the cost effectiveness of providing artificial shelter. Developing relationships between area of shade provided and the amelioration benefit achieved would allow the optimum provision of shade to be calculated.

5.4.2. Nutrition

Most heat stress in southern Australia is occurring during the months when the pasture is low quality and supplementary feed is often provided. A higher quality diet reduces the heat load associated with digestion, and therefore it is expected that providing a high-quality supplementary feed rather than roughage will reduce heat stress. The cost per MJ of ME purchased is similar for concentrate and roughage when calculated using 5-year average prices from SW Victoria (**Table** 0-1). However, concentrate is usually cheaper to feed out per tonne compared with roughage due to less bulk needed to be handled. While there is usually less wastage with concentrates due to higher palatability, these factors are offset slightly by the lower storage cost of roughages which are typically stored in the paddock rather than a silo. Overall, these factors and the higher efficiency of utilisation of ME make concentrate a cheaper feed per MJ of net energy (NE) consumed (**Appendix 4**). In a pasture situation, supplement is fed to provide a target number of extra MJ for the animals, so comparison of feed sources on the cost per MJ of NE is relevant. Therefore, switching to concentrate from roughage will be cost effective unless the paddock feed supply is such that there is a shortage of fibre, which may affect if roughage is not supplemented in the diet.

Changing from feeding roughage to feeding concentrate will have no cost (or likely will reduce cost) for those who currently feed roughage (**Appendix 4**: Derivation of cost of supplement). However, a switch to containment feeding and substituting concentrate for dry paddock feed will increase costs. Providing the maintenance requirement for a 55 Kg animal in confinement is approximately $0.18/day. Therefore, joining in confinement for 5 weeks with an introductory period will cost approximately $8/ewe. This is the higher estimate of the increase in cost of feed associated with feeding sheep in confinement as it is likely that the ewes would be offered supplementary feed in the paddock. However, producers who are not currently set up for confinement feeding will also incur some capital expense associated with feeding, watering and containment infrastructure.

The efficiency of utilising a high-quality concentrate (13.0 MJ/kg) for maintenance as predicted by the feeding standards (SCA 1990: $k_m = 0.02 + 0.5$ M/D) is 76%, which compares with the efficiency of a roughage (9.1 MJ/kg) of 68%. This difference in efficiency of using ME as NE (NE: energy available for maintenance) means that an extra 0.15 MJ of heat is produced per MJ of NE consumed. For a 55 Kg animal requiring 7.5 MJ of ME for maintenance (equivalent to 5 MJ of NE) this is 0.75 MJ less heat generated if the whole diet was concentrate rather than roughage. For a farmer feeding 1 Kg/hd/week of roughage, switching to concentrate would reduce heat production by 0.13 MJ/d. These numbers provide a realistic range over which farmers might adjust feeding.

The results from

Table 0-6 can be used to estimate the amelioration associated with a change in ambient temperature by assuming that the changing climate scenario is equivalent to changing ambient temperature. There is some error involved as the climate scenario also adjusted humidity, but the extrapolation will give an approximation.

Table 0-6 shows that a +1 °C increase in temperature alters the cost of heat stress by 18%. Combining that value with the two scenarios of concentrate feeding and the two scenarios of temperature equivalence generates a range of amelioration achieved of between 5% and 50% (

Table 0-11). The lower level of amelioration is achieved with little or no cost for those feeding roughage; however, the higher amelioration likely involves feeding concentrate in substitution for paddock feed, which will increase costs up to $8/hd.

Table 0-11: Reduction in heat production (MJ/d) and the equivalence of heat production to ambient temperature, as well as the possible level of amelioration (%) that could be achieved by increasing diet quality.

Temp/MJ	0.13		0.75	
	%	MJ/d	%	MJ/d
2.0 °C / MJ	5%	0.26	27	1.5
3.5 °C / MJ	8%	0.46	47	2.6

5.4.3. Containment mating

Mating in confinement provides opportunity to control the diet of the ewes and provide a high level of shelter, while tactically using water to reduce heat load. This opportunity is not available in an extensive paddock situation; however, if artificial shade was installed, irrigating the shade structure with sprinklers on extreme days would be a low-cost option if water was available. This scenario would likely increase the level of amelioration achieved, possibly up to 100% in low humidity conditions.

The increased feeding cost in containment is likely to be in the range $5 to $8/ewe for the joining period, plus additional costs associated with providing artificial shelter; $1 to $2/ewe depending on stocking density. This cost may be recouped from the reduced heat stress; however, the capital cost of the infrastructure would need to be justified through extra carrying capacity from deferring germinating pastures to increase leaf area.

5.4.4. Time of lambing

It has been widely analysed and concluded that time of lambing (TOL) occurs in late winter and spring, which closely matches animal energy requirements with the pasture supply in southern Australia (Warn et al., 2006). However, many producers continue to lamb in autumn due to other advantages which have not been included in this economic analysis.

Lambing in autumn leads to greater exposure to heat stress during the important phases of the reproductive cycle, and shifting to a spring/early summer lambing will reduce the impact of heat stress on reproduction. The approach taken for this analysis was a comparison of the climate scenarios for different times of lambing to quantify the change in incentive to move time of lambing in response to increased heat stress. This is based on the presumption that farmers are currently making informed decisions about lambing time and they might change if increasing heat stress provides incentive. The comparison made was the current (median) time of lambing against joining in May and lambing in October. This is a very late lambing for southern winter rainfall areas for all but the longest growing season environments. However, it may be more practical for summer growing areas which would have an expectation of green feed post-lambing.

In all but one region evaluated, the extra incentive to change TOL in the +1 °C scenario was $1/ewe or less (**Figure 5-2**). However, for the +3 °C scenario, 30% of producers incur an extra cost of $5/ewe and 10% of producers incur an extra cost of $8/ewe or more. This cost incentive may be sufficient for some producers to change; However, selection of TOL is still likely to be determined by matching feed supply with feed demand.

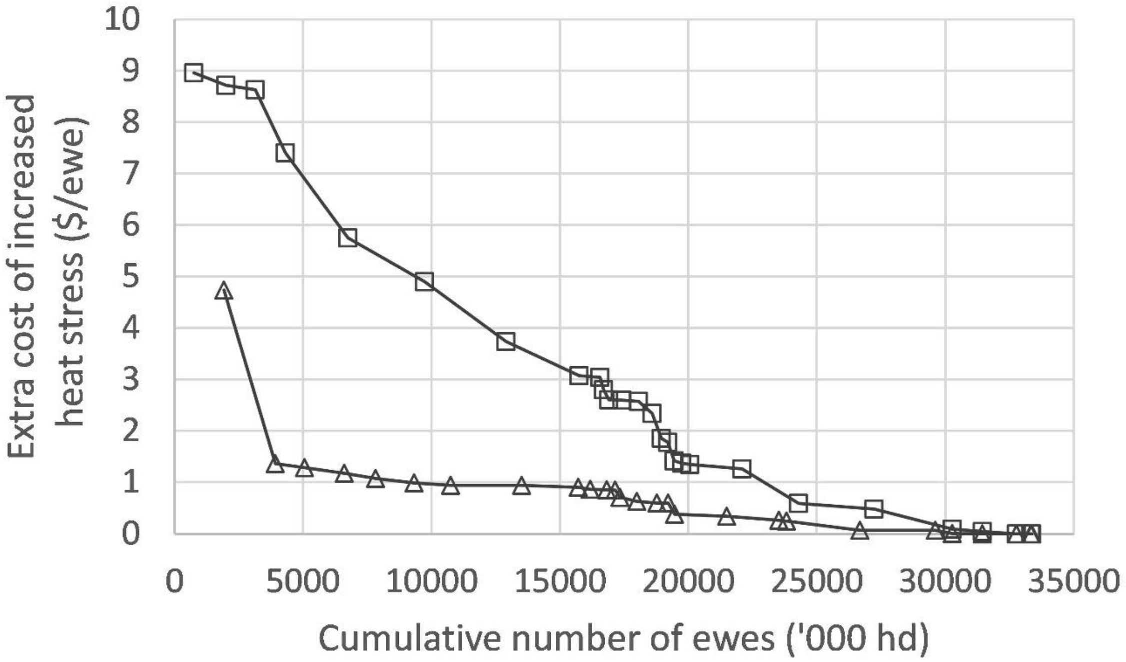

Figure 0-2. The extra incentive to change time of lambing for the +1 °C (Δ) and the +3 °C (□) climate scenarios. Valued at lamb at $6/kg with the best bet model (all assumptions).

5.4.5. Extend joining

Extending joining is a tactic that farmers could implement if hot weather is experienced during the joining period and a high level of conception failure is expected. This is contrary to general industry extension (i.e. Making More from Sheep, Module 10) which advocates condensed joining, with the current recommendation to join for five weeks rather than the historically common eight-week joining period. The benefits of a condensed joining relate to the improved ability to manage ewe nutrition during pregnancy and lactation, and lower weaner mortality due to less range in weaner liveweight within the drop.

Advocating a longer joining will result in confusing messages for the farming community; however, it may be a useful tactic in specific years for autumn lambing flocks where there has likely been conception failure due to extra hot weather during the joining period. In these years, extending joining for another cycle would allow those ewes another opportunity to conceive. Extending joining for an autumn lambing is a defacto way of lambing later, and the analyses mentioned previously indicate later lambing is more profitable. However, it is unlikely to be profitable for spring lambing flocks for which the later born lambs will have low weaning weight and increased post-weaning mortality associated with lack of green feed post-weaning (Campbell *et al.* 2014).

5.4.6. Time of shearing

Farmer selection of time of shearing is a trade-off between many factors including:

- TOL, which is often selected on the basis of the feed supply. TOL has implications associated with not shearing in the period after mulesing while the mulesing wounds are healing. It also determines joining date that constrains shearing close to joining.

- Sale time of surplus sheep which is also affected by time of lambing.
- Wool quality. The discount for staple strength is affected by the time of shearing relative to the point of break in the wool. Shearing time also affects VM content.

Changing shearing time to optimise fleece length to reduce heat stress will be another factor for farmers to consider; however, the impacts on heat stress will need to be large for it to become the primary decision factor.

5.4.7. Genetic selection

McCrabb et al. (1993); McCrabb and Bortolussi (1996) have shown that heat tolerance is a repeatable trait and concluded there may be a genetic component which can be exploited to reduce the impact of heat stress without farmers having to change breed. This is consistent with the findings of Eady et al. (1991) who reported lower rectal temperatures in locally adapted Peppin Merino from NW Queensland compared to South Australian Merino, which were not adapted to heat stress.

Including a trait for heat tolerance in the breeding objective for Australian sheep may lead to faster adaptation to the hotter temperatures which are predicted for the agricultural regions of Australia. The cost of the inclusion is the direct cost of measurement and the opportunity cost of reduced selection pressure on other economically important traits. These costs are difficult to estimate without the heritability and correlation parameters and without knowledge of the selection criteria that might be used.

The potential net benefit of including a heat tolerance trait was estimated ignoring the above costs and assuming that the rate of genetic gain in heat tolerance would be similar to the rate of genetic gain of other traits over a period of 10 years. If it is assumed that:

1) the 5% most heat tolerant ewes in the Australian flock would not be affected by the temperature scenarios examined in this project, and
2) that the gain in heat tolerance will be similar to the rate of gain for CFW, NLW, SS & FEC

If this is the case, then it was derived that 60% of the cost of heat stress could be ameliorated in a 10-year period if studs could efficiently select for heat tolerance as part of a balanced breeding objective (see **Appendix 5** for the derivation and assumptions).

5.4.8. Summary table

Table 0-12: Strategies evaluated to ameliorate the impacts of heat stress on reproduction.

Strategy	Potential range of amelioration	Time frame	Possible cost ($/ewe)	Comments
Shelter	0 – 50%		$1-$2	Cost and amelioration depends on animal behaviour related to seeking shade
Nutrition	5 – 50%		$0-$8	
Containment mating	Up to 100%		$7-$10	
Mating protocol	-			May be tactically useful in extreme years
Time of shearing	Minor			TOS is a system wide decision
Time of Lambing				Only relevant to a restricted number of producers
Genetic selection	60%	10 years	could be low	Requires a practical measurement protocol or genomic selection.

5.5. Research, development and extension budget

The justifiable research, development and extension (R, D & E) budget which could be allocated to this area was calculated as a reverse Benefit Cost Analysis (BCA). The proposed values of the R, D & E budget was calculated which would deliver a target Benefit Cost Return (BCR) ratio based on the research delivering amelioration strategies at a range of implementation costs and a range of effectiveness. Table 0-13 provides a summary of the data used for the following calculation.

The equation used, which can be rearranged to calculate the budget, was:

BCR = discounted sum of (net on-farm benefits attributable to research * level of adoption over time) * probability of success / PV of RD&E expenditure.

$$PV\ of\ R, D\ \&\ E\ budget = ((potential\ benefit * amelioration\ achieved * attribution * probability) \sum\text{_}years ▒ 〖adoption〗\text{_}n/((〖1+i)〗\text{^}n))/(Target\ BCR)$$

$$Potential\ benefit\ for\ a\ strategy = \sum\text{_}region ▒ 〖number\ ewes * scalar * attribution * ((〖BE\ cost〗\text{_}r * \%\ amelioration) - implementation\ cost\ of\ strategy)〗$$

$$Annualresearchbudget = (PVofbudget * i)/\left(1-(1+i)^{(yearsofresearch)}\right)$$

Table 0-13: Assumptions underpinning analysis of the justifiable R, D & E budget.

Parameter	Level
Proportion of heat stress ameliorated	25% 50% 100%
Implementation cost	\$0 to \$15
Attribute to research	100%
Probability of research success	25%
Length of research phase	5yrs
Adoption	
Peak level	25%
Lag to start of adoption	5 years
Peak adoption (after lag)	10 years
Disadoption period (after peak)	20 years
Target BCR	4

Using values from the best-bet model with lamb at \$6/kg and the +1 °C climate scenario, using figures from

Table 0-6, industry profitability would increase by \$203m/yr if; (1) it was expected that research could develop a strategy or technology which was 100% effective at ameliorating heat stress; and (2) it could be implemented on-farm with no cost, and was adopted by all farmers. Using the adoption and timeframe assumptions in Error! Reference source not found.**,** an annual research expenditure over five years of \$3.8 million would provide a BCR for the research of 4.0. However, if the technology developed only ameliorates half the impact of heat stress then the annual budget that would return a BCR of 4 is reduced to \$1.9 million. If there is an on-farm cost of implementing the technology then the benefit per ewe is reduced and it is only profitable for a proportion of farmers (**Figure** 0-1. Distribution of the cost of heat stress (\$/ewe) across the national flock. Best bet model, +1 °C scenario with lamb \$6/Kg.

5.6. Value of Amelioration Strategies

The second component of the analysis was a preliminary examination of the value that could be achieved from on-farm amelioration strategies which could be implemented to reduce the impact of heat stress on reproduction. The focus was on the potential cost of the amelioration and the proportion of the impact of heat stress that might be ameliorated. Therefore, this analysis was focused on strategies that could be developed through research and development (

Table 0-9).

Table 0-8 Total reduction in profit due to heat stress (per ewe) in each region for the standard price scenario (lamb $6/kg).

	Analysis scenario					
	Robust model (confident assumptions)			Best bet model (all assumptions)		
State Site	Current	+1 °C	+3 °C	Current	+1 °C	+3 °C
QLD						
Longreach	754 (13.8)	803 (14.7)	827 (15.1)	754 (13.8)	803 (14.7)	827 (15.1)
Cunnamulla	454 (10.1)	515 (11.5)	589 (13.2)	454 (10.1)	515 (11.5)	589 (13.2)
St George	2 (0.0)	12 (0.1)	93 (0.6)	2 (0.0)	12 (0.1)	93 (0.6)
NSW						
Wilcannia	3108 (10.8)	3394 (11.8)	3818 (13.2)	3108 (10.8)	3394 (11.8)	5690 (19.7)
Gunnedah	5 (0.2)	13 (0.4)	64 (2.0)	5 (0.2)	13 (0.4)	64 (2.0)
Armidale			12 (0.0)			12 (0.0)
Trangie		1 (0.0)	14 (0.1)		1 (0.0)	14 (0.1)
Dubbo	1530 (3.8)	2047 (5.1)	3499 (8.7)	1530 (3.8)	2047 (5.1)	3499 (8.7)
Griffith	119 (5.8)	139 (6.7)	185 (9.0)	322 (15.5)	339 (16.4)	380 (18.3)
West Wyalong	1643 (5.8)	1988 (7.0)	2634 (9.3)	4358 (15.4)	4661 (16.5)	5229 (18.5)
Young	2030 (2.5)	2780 (3.5)	5020 (6.3)	2030 (2.5)	2780 (3.5)	5020 (6.3)
VIC						
Walpeup	36 (0.4)	57 (0.7)	151 (1.8)	36 (0.4)	57 (0.7)	151 (1.8)
Bendigo	172 (1.6)	237 (2.2)	451 (4.2)	172 (1.6)	237 (2.2)	451 (4.2)
Shepparton	164 (2.8)	211 (3.6)	338 (5.8)	809 (13.8)	851 (14.5)	962 (16.4)
Hamilton	86 (0.1)	161 (0.2)	600 (0.6)	86 (0.1)	161 (0.2)	600 (0.6)
Ballarat	25 (0.7)	40 (1.1)	78 (2.1)	25 (0.7)	40 (1.1)	78 (2.1)
SA						
Minnipa	335 (4.7)	404 (5.7)	523 (7.4)	984 (13.9)	1045 (14.7)	1150 (16.2)
Rosedale	148 (3.5)	176 (4.2)	232 (5.6)	543 (13.0)	568 (13.6)	618 (14.8)
Renmark	725 (7.5)	808 (8.4)	975 (10.1)	725 (7.5)	808 (8.4)	975 (10.1)
Struan	1003 (2.0)	1255 (2.5)	1838 (3.7)	4405 (8.8)	6784 (13.5)	7296 (14.5)
WA						
Geraldton	533 (6.7)	586 (7.4)	746 (9.4)	941 (11.8)	991 (12.4)	1531 (19.2)
Northam	699 (9.3)	794 (10.5)	963 (12.8)	1131 (15.0)	1219 (16.2)	1788 (23.7)
Katanning	439 (4.2)	544 (5.3)	801 (7.7)	1021 (9.9)	1119 (10.8)	1914 (18.5)
Esperance	609 (2.0)	711 (2.4)	991 (3.3)	609 (2.0)	711 (2.4)	991 (3.3)

Note: to generate the value for the national flock each region is scaled based on the number of ewes in each state compared with the regions evaluated in that state.

), and the number of ewes impacted is reduced.

The cost of heat stress varies between regions from $0 to $20/hd (**Table** 0-8). This indicates that the worst affected regions could spend more than $7.50/ewe and still make a return if 50% of the impact of heat stress could be ameliorated. Whereas other regions will not adopt a technology even if the cost is as little as $1/ewe.

Combining scenarios for the proportion of the impact ameliorated and the on-farm cost of implementing the technology allows generation of the annual research budget that would return a BCR of 4 (Figure 0-3). The budget is very sensitive to the proportion of the heat stress ameliorated, especially as the on-farm implementation cost increases. Further scenarios in (**Appendix 6: Impacts of heat stress on number of lambs weaned** calculated for each region and each climate scenario.

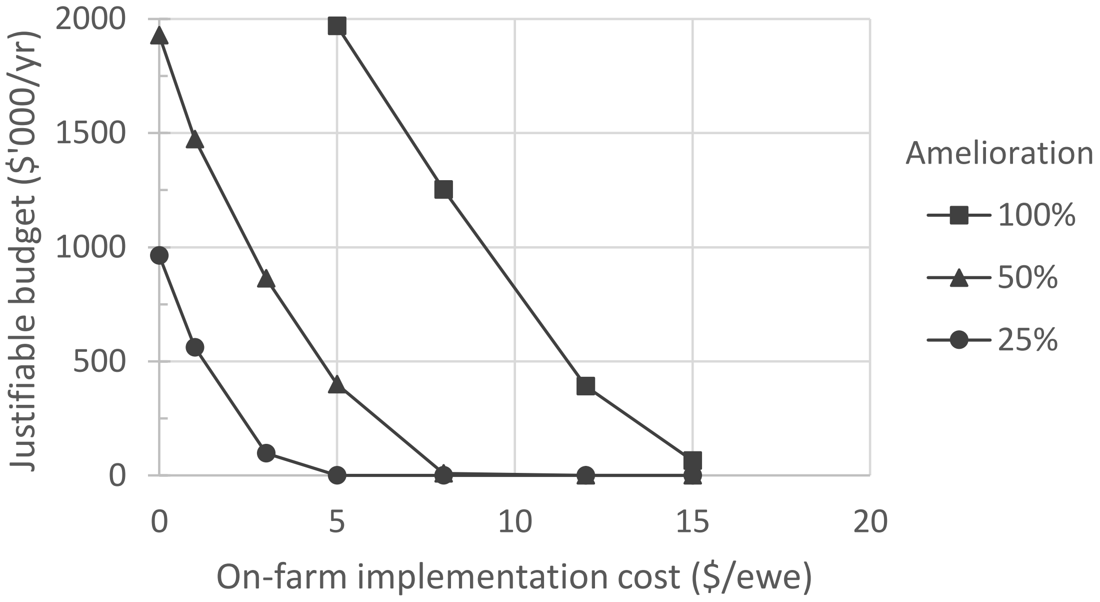

Figure 0-3: The justifiable annual research budget if developing technology with varying efficiency at ameliorating heat stress and a range of implementation costs ($/ewe). Best-bet model, $6/Kg for lamb and +1 °C climate scenario.

5.7. Summary of economic impact of heat stress

The cost of heat stress calculated in this project is comparable to the results of Sackett et al. (2006), where a cost was put on the reduced production due to disease and added the on-farm costs associated with ameliorating the disease. The current study only valued the reduction in production based on the presumption that farmers currently do not increase costs to ameliorate heat stress. In both the Sackett et al. (2006) and the current analysis, the value reported is the increase in profit expected if the disease or the stress could be managed 100% effectively for no cost, that is, the disease or stress would disappear and stop being a problem. The Sackett et al. (2006) analysis was carried out for a lamb price of $2.90/kg and a national ewe flock of 70 million ewes. This is a larger flock than current and for comparison purposes their published results have been scaled by 47% to generate an estimate equivalent to the flock size used in this analysis (33.3 million ewes).

The analysis of Young et al. (2014) that examined the cost of lamb mortality from birth to weaning is not fully compatible as that study used the increase in profit expected from improving survival from current levels to an expected realistically achievable level was quantified. For example, the reduced level of twin lamb mortality was approximately one third of the current level, so the value calculated using that methodology is approximately two thirds of the value if following the methodology of this project, as well as in Sackett et al. (2006). The Young et al. (2014) analysis was carried out with a lamb price of $5/kg, and a ewe flock of 42.9m ewes. To convert the published values to a comparable flock size the values were scaled by 78% to correct for flock size, but this was offset by the scaling carried out to reflect the reduced range that was valued.

Based on these adjustments and comparing equivalent price scenarios with the best bet estimate of this project for the +1 °C scenario, the impact of heat stress on reproduction is below that of worms, flies, and the Young *et al.* (2014) estimate of lamb mortality, ewe mortality and conception and early embryo mortality, but above lice, post-weaning mortality, ryegrass and phalaris toxicity, enteritis, arthritis, footrot and OJD (

Table 0-14). This indicates that heat stress is a major factor in the profitability of the Australian sheep industry.

Table 0-14: Comparison of impact of heat stress (best bet model, +1 °C scenario) with impacts of other studies adjusted to similar flock size and equivalent methodology.

Disease or stress	\$3/kg[1]	\$5/kg[2]
Worms	175.0	
Flies	132.8	
Lamb mortality – overall	84.0	
Single		302.1
Twin		569.9
Ewe mortality		345.6
Conception & embryo mortality		293.5
Heat stress	**90.6**	**157.8**
Lice	58.2	
PW mortality	42.5	50.4
PRGT	30.0	
Bacterial enteritis	14.0	
Arthritis	12.3	
Footrot	8.7	
OJD	2.1	
Phalaris Tox	0.8	

Sources: [1] Sackett et al. 2006. Values scaled by 47%; [2] Young et al. 2014. Values scaling varied with trait between 105% to 125%.

There is a large inconsistency between the study of Sackett et al. (2006) and the study of Young et al. (2014) in terms of lamb mortality. An approximate extrapolation of the studies to an equivalent price shows that the values of (Young et al., 2014) are about five time the value of Sackett et al. (2006). This is related to differences in the assumed value of extra lambs surviving. Little detail is provided in the Sackett et al. (2006) report to recreate the calculations carried out so it is not possible to reconcile the different values. Although the study of Young et al. (2014) includes costs associated with weaning more lambs (feed requirement of the extra lambs weaned, extra feed requirement of the extra lactating ewes), these are not mentioned in the Sackett et al. (2006) analysis, and therefore, it could be expected that the Young et al. (2014) values should be lower.

In each of the analyses, there may be some underestimation of the cost of the disease or heat stress if farmers are currently altering land-use or enterprise scale to ameliorate the stress (i.e. they may be choosing to run fewer sheep as a result of the disease, heat stress or mortality). The extra profit that could be gained from reversing those decisions in the absence of the stress has not been evaluated.

The amelioration strategies were very difficult to quantify as there was very little data on which to base what is required or the effectiveness. However, some best estimates of the implementation costs varied from $0 up to $10/ewe and the expected level of amelioration varied from 0 up to 100%. These calculations provided a range of values with which to carry out a reverse benefit cost analysis to quantify the research budget that could be justified if strategies could be developed. If it is expected that strategies that are 50% effective and cost $5/ewe could be implemented then an annual budget of $500K would deliver a BCR on funds invested of 4.0.

The analysis reported here did not address the impact of climate change on the potential carrying capacity of farms. While the resulting change in stocking rate may have a bigger impact on livestock profitability than the effect of reduced reproductive performance due to heat stress (Thamo et al., 2017), the two impacts are likely to be additive. Therefore, the values calculated in this project could be combined with results from any analysis carried out that quantified the impacts of climate change on potential carrying capacity.

6. Prioritising research, development and extension to alleviate the impacts of heat stress

Prioritising research focus, in terms of which priority area should be tackled first or receive more funding, is complicated by two factors; (1) the need to address significant knowledge gaps in our understanding as the impacts of heat stress on sheep homeothermy, behaviour and fertility, especially under free-ranging conditions; and (2) the urgent need to develop strategies to reduce the impacts of heat stress on ewe and ram fertility and welfare, strategies which can be adopted by farmers to mitigate the risk of heat induced reproductive wastage. Further compounding this problem is the fact that increased understanding of the impacts of heat stress would facilitate the development of amelioration strategies, and that non-invasive remote sensing technologies to determine homeothermy of free-ranging sheep are currently lacking. The ideal approach to this conundrum is to develop a significant long-term program of multi-disciplinary research involving scientists and industry partners. This program of research should seek to fill the knowledge gaps identified, whilst also developing technologies and strategies that can be rapidly adopted by the industry, as well as longer term solutions (i.e. shade, genetic selection).

The priority of any research is to develop practical solutions to facilitate homeothermy in ewes and rams, maintain fertility and fecundity of sheep exposed to thermal strain, and identify phenotypic and genetic markers of heat tolerance and reproductive resilience under thermal strain. Alongside of this, there is a priority to maximise producer adoption, which may be achieved through demonstrating the impacts of heat stress on ewe and ram fertility under field conditions, as well as creating production demonstration sites which provide producers with evidence and confidence that the amelioration strategies work, and guidance as to how to adopt them (if required).

One approach to ranking research focussed on protecting the sheep industry from the detrimental impacts on heat stress is to do so based on the following desirable outcomes:

1. Increased fertility and fecundity of ewes exposed to heat stress conditions (oestrus expression, conception and pregnancy rates and litter size)
2. Increasing the birthweight and survival of lambs born to ewes exposed to heat stress during pregnancy
3. Increasing sperm quality and production, as well as mating behaviour, of rams exposed to heat stress
4. Establishing the impact of heat stress on developmental programming of progeny, and preventing this from occurring.
5. Optimising commercial adoption of mitigation strategies through increased understanding of the extent of the problem, and commercial validation of any mitigation strategies.

When this approach is considered, the four research priorities are as follows in order of urgency, practicality and likely time to outcome delivery:

1. Establishing mitigation strategies which promote homeothermy and reproductive function of ewes and rams under thermal strain (i.e. nutrition, shade, wool cover, mating protocols)
2. Understanding the impact of ambient conditions on the behaviour, resource use and fertility of sheep under typical production systems, and identify differences between individuals (behavioural, physiological, molecular) in their ability to thermoregulate and maintain reproduction under thermal strain.
3. Modifying the environment to reduce the severity of thermal strain (use of shade, establishing cooler microclimates, establishing THI thresholds, adoption of containment housing systems)
4. Selection for physiological and behavioural adaptions that promote heat resilience without impairing productivity.

It is worth noting that the achievement of most of these research outcomes would be facilitated by the development of non-invasive remote sensors that allow temperature, behaviour and fertility to be monitored in free-ranging ewes and rams. Such sensors may have commercial benefits, particularly for rams, thus enabling producers to intervene when ram performance is compromised, as well as establishing the impacts of heat stress on progeny performance. Secondary stages of any research should involve commercial validation in a range of production systems (containment housing, pasture and rangeland), with consideration given to the development of production demonstration sites, resulting in wide scale commercial adoption within 5 to 10 years.

7. Summary and conclusions

Stage one of this report provided clear evidence that the reproductive performance of the Australian sheep flock is significantly impaired by heat stress under current climate conditions. Specifically, temperatures experienced by flocks during the period when a significant proportion of the Australian flock is joined (November to March) reduce the number of ewes lambing and the numbers of lambs born. The annual cost to the industry due to reproductive wastage is calculated to be $97 million (robust model; fewer lambs born) or $168 million (best bet model; fewer lambs born and weaned) annually. These impacts will worsen under projected changes to climate, both in terms of number of potential lambs lost and the economic impact. However, as outlined in the preceding document it is also clear that significant knowledge gaps exist in our understanding of how, and to what extent, heat stress impairs the reproductive output and efficiency of the Australian sheep flock. Based on this, it is also clear that a significant body of research is essential to develop management strategies which will allow Australian sheep producers to protect their flocks from the significant risk associated with heat stress.

8. References

Croker, K., Curtis, K. & Speijers, J. 2009. Times of lambing in Australian flocks: 2005 to 2007. *Wool Desk Report - Feburuary 2009.* Deparment of Agriculture and Food. Perth, Western Australia.

Eady, S., O'Rourke, P. & Connelly, P. 1991. Comparison of wool production and reproductive rate of South Australian strain Merinos and locally bred Peppin Merinos in the semi-arid tropics of Queensland. *Australian Journal of Experimental Agriculture,* 31**,** 737-743.

Lindsay, D. R., Knight, T. W., Smith, J. F. & Oldham, C. M. 1975. Studies in ovine fertility in agricultural regions of Western Australia: ovulation rate, fertility and lambing performance. *Australian Journal of Agricultural Research,* 26**,** 189-198.

McCrabb, G., McDonald, B. & Hennoste, L. 1993. Lamb birthweight in sheep differently acclimatized to a hot environment. *Australian Journal of Agricultural Research,* 44**,** 933-943.

McCrabb, G. J. & Bortolussi, G. 1996. Placental growth and the ability of sheep to thermoregulate in hot environment. *Small Ruminant Research,* 20**,** 121-127.

Oldham, C., Thompson, A., Ferguson, M., Gordon, D., Kearney, G. & Paganoni, B. 2011. The birthweight and survival of Merino lambs can be predicted from the profile of liveweight change of their mothers during pregnancy. *Animal Production Science,* 51**,** 776-783.

Sackett, D., Holmes, P., Abbott, K., Jephcott, S. & Barber, M. 2006. Assessing the economic cost of endemic disease on the profitability of Australian beef cattle and sheep producers. *MLA Report AHW,* 87.

Thamo, T., Addai, D., Pannell, D. J., Robertson, M. J., Thomas, D. T. & Young, J. M. 2017. Climate change impacts and farm-level adaptation: Economic analysis of a mixed cropping–livestock system. *Agricultural systems,* 150**,** 99-108.

van Wettere, W. , Culley, S., Gatford, K., Kind. K., Lee, S., Leu, S., Swinbourne, A., Westra, S., Hayman, P., Kleemann, D., Kelly, J., Thomas, D., Weaver, A. & Walker, S. 2019. Effects of heat stress, and climate change scenarios on reproductive performance of the Australian sheep flock. Milestone Report to MLA. Project L.LSM.0024 25th October, 2019.

Warn, L., Webb Ware, J., Salmon, L., Donnelly, J. & Alcock, D. 2006. Analysis of the profitability of sheep wool and meat enterprises in southern Australia. *Sheep Co-operative Research Centre: Armidale, NSW*.

Young, J., Trompf, J. & Thompson, A. 2014. The critical control points for increasing reproductive performance can be used to inform research priorities. *Animal Production Science,* 54**,** 645-655.

Appendix 1: Production assumptions

Table 0-1: Current production levels and impact of heat stress on EL-number of ewe lambing (‘000 hd), LB-number of lambs born (‘000 hd) and BW-birth weight (%) for the 3 climate scenarios (current, +1 °C, +3 °C). Source: van Wettere et al. (2019) Table 3-3 and 3-4.

			Current production		Climate Scenario (production impact compared with ‘no heat stress’)								
					Current			+1°C			+3°C		
State	Site	Joining	Ewes (‘000)	Lambs marked (‘000)	EL (‘000)	LB (‘000)	BW (%)	EL (‘000)	LB (‘000)	BW (%)	EL (‘000)	LB (‘000)	BW (%)
QLD	Longreach	Mar	54.6	30.9	-9.2	-12.0	0	-9.8	-12.8	0	-10.1	-13.2	0
	Cunnamulla	Mar	44.7	22.2	-5.6	-7.2	0	-6.3	-8.2	0	-7.2	-9.4	0
	St George	May	154.6	138.8	0	0	0	-0.1	-0.2	0	-1.1	-1.5	0
NSW	Wilcannia	Feb	288.2	242.3	-38.1	-49.4	0	-41.6	-54.0	0	-46.8	-60.7	-15.0%
	Gunnedah	Apr	31.9	33.8	-0.1	-0.1	0	-0.2	-0.2	0	-0.8	-1	0
	Armidale	Apr	298.7	278.2	0	0	0	0	0	0	-0.1	-0.2	0
	Trangie	May	149.1	144.5	0	0	0	0	0	0	-0.2	-0.2	0
	Dubbo	Mar	401.8	410.7	-18.8	-24.3	0	-25.1	-32.5	0	-42.9	-55.6	0
	Griffith	Dec	20.7	20.1	-1.5	-1.9	-17.5%	-1.7	-2.2	-17.5%	-2.3	-2.9	-17.5%
	West Wyalong	Dec	283.1	269.7	-20.2	-26.1	-17.5%	-24.4	-31.6	-17.5%	-32.3	-41.9	-17.5%
	Young	Mar	800.7	802.9	-24.9	-32.3	0	-34.1	-44.2	0	-61.6	-79.8	0
VIC	Walpeup	Apr	84.1	86.5	-0.4	-0.6	0	-0.7	-0.9	0	-1.8	-2.4	0
	Bendigo	Mar	108.5	100.1	-2.1	-2.7	0	-2.9	-3.8	0	-5.5	-7.2	0
	Shepparton	Dec	58.7	64.1	-2.0	-2.6	-17.5%	-2.6	-3.4	-17.5%	-4.1	-5.4	-17.5%
	Hamilton	Apr	1 068.5	1069.5	-1.1	-1.4	0	-2.0	-2.6	0	-7.4	-9.5	0
	Ballarat	May	37.5	40.7	-0.3	-0.4	0	-0.5	-0.6	0	-1.0	-1.2	0
SA	Minnipa	Dec	70.9	64.5	-4.1	-5.3	-17.5%	-5.0	-6.4	-17.5%	-6.4	-8.3	-17.5%
	Rosedale	Dec	41.7	39.3	-1.8	-2.4	-17.5%	-2.2	-2.8	-17.5%	-2.8	-3.7	-17.5%
	Renmark	Feb	96.4	92.7	-8.9	-11.5	0	-9.9	-12.9	0	-12.0	-15.5	0
	Struan	Dec	502.7	552.3	-12.3	-15.9	-12.5%	-15.4	-19.9	-17.5%	-22.5	-29.2	-17.5%
WA	Geraldton	Feb	79.7	66.3	-6.5	-8.5	-12.5%	-7.2	-9.3	-12.5%	-9.1	-11.9	-20.0%
	Northam	Feb	75.4	70.1	-8.6	-11.1	-12.5%	-9.7	-12.6	-12.5%	-11.8	-15.3	-20.0%
	Katanning	Feb	103.4	94.6	-5.4	-7.0	-12.5%	-6.7	-8.6	-12.5%	-9.8	-12.7	-20.0%
	Esperance	Feb	302.7	276.1	-7.5	-9.7	0	-8.7	-11.3	0	-12.2	-15.8	0
TAS	Launceston	Apr	19.7	22.1	0	0	0	0	0	0	0	0	0
	Hobart	May	1.1	0.343	0	0	0	0	0	0	0	0	0

Appendix 2: MIDAS lamb values used

Table 0-1: Value of an extra lamb. Derived from Young et al., 2014. MIDAS modelling for SW Victoria.

	Lamb price ($/kg DW)						
	$2	$3	$4	$5	$6	$7	$8
Merino[1]	15	27	39	52	65	78	91
Merino-Terminal[1]	24	43	56	74	100	111	129.5
Maternal[1]	20	43	54	70	87	105	122.5

[1] These values are the values for an extra lamb weaned if that lamb was achieved from a combination of increased conception (fertility and fecundity) and increased survival.

Colour coding:

Values published in Young *et al.* 2014.
🟩 Extrapolated from the value at $5/kg, using 25% per $1/kg

Appendix 3: Calculating survival from birthweight

Equations to estimate survival from birthweight. Source: Oldham et al. (2011).
3-step process following a statistical analysis of transformed survival data. Single and twin lamb survival is calculated separately, as well as combined, based on the proportion of lambs born as twins (33%).

1) Calculate transformed survival using quadratic function.

$$Single\ survival, transformed\ SSt = a + \text{〖}bBW\text{〗}\_s + c\ \text{〖}BW\text{〗}\_s\text{^}2$$

$$Twin\ survival, transformed\ TSt = a + b\ \text{〖}BW\text{〗}\_t + c\ \text{〖}BW\text{〗}\_t\text{^}2 - d$$

where: a = -7.09, b = 3.03, c = -0.265 & d = 0.712

Coefficient 'a' was calibrated so that the standard no-stress survival (75%) was achieved with the average birthweight (5.3kg) and the expected difference in birthweight between single and twins (1.1kg).

2) Back transform the survival to generate actual survival

$$Singlesurvival(SS) = 1/\left(1 + e^{(-SSt)}\right)$$

$$Twinsurvival(TS) = 1/\left(1 + e^{(-TSt)}\right)$$

3) Calculate the weighted average lamb survival.

$$Averagelambsurvival = SS - proportiontwinsx(SS - TS)$$

Appendix 4: Derivation of cost of supplement

Table 0-1: Assumptions and calculation underpinning the cost of providing a higher quality diet.

		Concentrate[1]	Roughage[2]
Feed quality	MJ of ME/kg	13	9.1
Efficiency (k_m)	%	0.76	0.682
Net energy	MJ of NE/kg	9.88	6.2062
Heat produced	MJ/MJ of NE	0.32	0.47
Extra heat produced	MJ/MJ of NE		0.15
Cost per tonne			
Purchase	$/t	380	274
Storage	$/t	20	0
Feeding out	$/t	50	75
Wastage	%	15%	20%
Cost per MJ			
ME purchased	$/MJ of ME	$0.029	$0.030
ME consumed	$/MJ of ME	$0.041	$0.048
NE consumed	$/MJ of NE	$0.054	$0.070

[1] Concentrate based on barley (13.0 MJ/kg and $380/t).

[2] Roughage based on hay (9.1 MJ/t and $275/t).

Cereal hay and Barley quality was the average of 13 years from 05/06 to 17/18 from: www.feedtest.com.au/index.php/about/feedtest-information

Hay price relative to grain price based on 5yr average prices to Dec19 for SW Victoria. Source: Dairy Australia – Hay & grain reports: www.dairyaustralia.com.au/industry/farm-inputs-and-costs/hay-and-grain-report-overview

Appendix 5: Derivation of genetic gain

Comparison of the progress made by a stud (that has a broad breeding objective) in 4 of the traits that they are selecting for (CFW, NLW, SS & FEC) relative to the range in the Australian industry (based on the range in the SG percentile bands from 50% to 5%). Used as an indicator of the potential gain that may be achieved by selecting for heat tolerance.

Table 0-1: Derivation of assumptions underpinning the value of genetic selection.

Trait	SG percentile bands[1]			Gain made by stud[2]	
	50%	5%	Difference (50% to 5%)	in 10 yrs.	% of industry range
CFW	13.9	26.9	13.0	6.1	47%
SS	0.5	4.9	4.4	2.2	50%
NLW	1.0	10.0	9.0	9.1	101%
FEC	-15.0	-61.0	-46.0	-18.7	41%
Average					60%

[1]Source: http://sgsearch.sheepgenetics.org.au/Search/Percentiles.aspx?AnalysisId=5

[2]Source: Merinotech WA, 2008 to 2018 ASBVs from MerinoSelect analysis 11 Nov 2019

Appendix 6: Impacts of heat stress on number of lambs weaned calculated for each region and each climate scenario.

		'No Stress'		Analysis scenario								
				Robust model (confident assumptions)			Best bet model (all assumptions)			May joining		
State	Site	born ('000)	Lambs weaned ('000)	Current	+1 °C	+3 °C	Current	+1 °C	+3 °C	Current	+1 °C	+3 °C
QLD	Longreach	52.8	39.6	9.0 (16.5%)	9.6 (17.5%)	9.9 (18.1%)	9.0 (16.5%)	9.6 (17.5%)	9.9 (18.1%)	0.7 (1.2%)	1.4 (2.7%)	3.6 (6.6%)
	Cunnamulla	36.5	27.4	5.4 (12.1%)	6.1 (13.7%)	7.0 (15.7%)	5.4 (12.1%)	6.1 (13.7%)	7.0 (15.7%)	0.0 (0.0%)	0.1 (0.1%)	0.5 (1.1%)
	St George	183.2	137.4	0.0 (0.0%)	0.1 (0.1%)	1.1 (0.7%)	0.0 (0.0%)	0.1 (0.1%)	1.1 (0.7%)	0.0 (0.0%)	0.1 (0.1%)	1.1 (0.7%)
NSW	Wilcannia	369.3	276.9	37.1 (12.9%)	40.5 (14.0%)	45.5 (15.8%)	37.1 (12.9%)	40.5 (14.0%)	67.9 (23.5%)	0.3 (0.1%)	0.4 (0.1%)	1.6 (0.5%)
	Gunnedah	44.7	33.5	0.1 (0.2%)	0.2 (0.5%)	0.8 (2.4%)	0.1 (0.2%)	0.2 (0.5%)	0.8 (2.4%)	0.1 (0.2%)	0.2 (0.5%)	0.8 (2.4%)
	Armidale	367.2	275.4			0.1 (0.0%)			0.1 (0.0%)			0.1 (0.0%)
	Trangie	190.7	143.1		0.0 (0.0%)	0.2 (0.1%)		0.0 (0.0%)	0.2 (0.1%)		0.0 (0.0%)	0.2 (0.1%)
	Dubbo	566.5	424.8	18.3 (4.5%)	24.4 (6.1%)	41.7 (10.4%)	18.3 (4.5%)	24.4 (6.1%)	41.7 (10.4%)			0.2 (0.1%)
	Griffith	28.4	21.3	1.4 (6.9%)	1.7 (8.0%)	2.2 (10.7%)	3.8 (18.5%)	4.0 (19.5%)	4.5 (21.9%)		0.0 (0.0%)	0.0 (0.1%)
	West Wyalong	382.1	286.6	19.6 (6.9%)	23.7 (8.4%)	31.4 (11.1%)	52.0 (18.4%)	55.6 (19.6%)	62.4 (22.0%)			0.2 (0.1%)
	Young	1092.1	819.1	24.2 (3.0%)	33.2 (4.1%)	59.9 (7.5%)	24.2 (3.0%)	33.2 (4.1%)	59.9 (7.5%)			0.1 (0.0%)
VIC	Walpeup	114.7	86.1	0.4 (0.5%)	0.7 (0.8%)	1.8 (2.1%)	0.4 (0.5%)	0.7 (0.8%)	1.8 (2.1%)	0.4 (0.5%)	0.7 (0.8%)	1.8 (2.1%)
	Bendigo	134.9	101.2	2.1 (1.9%)	2.8 (2.6%)	5.4 (5.0%)	2.1 (1.9%)	2.8 (2.6%)	5.4 (5.0%)			0.0 (0.0%)
	Shepparton	87.2	65.4	2.0 (3.3%)	2.5 (4.3%)	4.0 (6.9%)	9.6 (16.4%)	10.1 (17.3%)	11.5 (19.5%)			
	Hamilton	1413.1	1059.8	1.0 (0.1%)	1.9 (0.2%)	7.2 (0.7%)	1.0 (0.1%)	1.9 (0.2%)	7.2 (0.7%)	1.0 (0.1%)	1.9 (0.2%)	7.2 (0.7%)
	Ballarat	54.1	40.6	0.3 (0.8%)	0.5 (1.3%)	0.9 (2.5%)	0.3 (0.8%)	0.5 (1.3%)	0.9 (2.5%)			
SA	Minnipa	90.5	67.8	4.0 (5.6%)	4.8 (6.8%)	6.2 (8.8%)	11.7 (16.6%)	12.5 (17.6%)	13.7 (19.3%)	0.1 (0.1%)	0.1 (0.1%)	0.4 (0.6%)
	Rosedale	54.2	40.7	1.8 (4.2%)	2.1 (5.0%)	2.8 (6.6%)	6.5 (15.5%)	6.8 (16.3%)	7.4 (17.7%)	0.0 (0.0%)	0.0 (0.1%)	0.0 (0.1%)
	Renmark	133.9	100.4	8.6 (9.0%)	9.6 (10.0%)	11.6 (12.1%)	8.6 (9.0%)	9.6 (10.0%)	11.6 (12.1%)	0.1 (0.1%)	0.1 (0.1%)	0.2 (0.2%)
	Struan	745.0	558.7	12.0 (2.4%)	15.0 (3.0%)	21.9 (4.4%)	52.5 (10.5%)	80.9 (16.1%)	87.0 (17.3%)		0.0 (0.0%)	0.2 (0.0%)
WA	Geraldton	96.0	72.0	6.4 (8.0%)	7.0 (8.8%)	8.9 (11.2%)	11.2 (14.1%)	11.8 (14.8%)	18.3 (22.9%)	0.3 (0.4%)	0.6 (0.7%)	1.3 (1.6%)
	Northam	103.6	77.7	8.3 (11.1%)	9.5 (12.6%)	11.5 (15.2%)	13.5 (17.9%)	14.5 (19.3%)	21.3 (28.3%)	0.0 (0.1%)	0.1 (0.2%)	0.4 (0.6%)
	Katanning	131.8	98.9	5.2 (5.1%)	6.5 (6.3%)	9.6 (9.2%)	12.2 (11.8%)	13.3 (12.9%)	22.8 (22.1%)		0.0 (0.0%)	0.1 (0.1%)
	Esperance	374.1	280.6	7.3 (2.4%)	8.5 (2.8%)	11.8 (3.9%)	7.3 (2.4%)	8.5 (2.8%)	11.8 (3.9%)	0.2 (0.1%)	0.6 (0.2%)	1.3 (0.4%)
TAS	Launceston	29.2	21.9									
	Hobart	0.5	0.3									

Appendix 7: Justifiable research budget

Table 0-1: Research budget that returns a BCR of 4. Current climate scenario, using the best-bet model to calculate the impact of heat stress for a range of implementation costs and a range of amelioration levels achieved from the research. Lamb price $6/kg.

	Amelioration effectiveness		
Implementation cost	25%	50%	100%
$0	797	1594	3187
$1	426	1147	2732
$3	50	614	1973
$5	0	203	1466
$8	0	0	760
$12	0	0	200
$15	0	0	12

Table 0-2: Research budget that returns a BCR of 4. Climate scenario +1°C, using the best-bet model to calculate the impact of heat stress for a range of implementation costs and a range of amelioration levels achieved from the research. Lamb price $6/kg.

	Amelioration effectiveness		
Implementation cost	25%	50%	100%
$0	964	1928	3856
$1	562	1473	3389
$3	98	864	2562
$5	0	400	1969
$8	0	8	1253
$12	0	0	391
$15	0	0	66

Table 0-3: Research budget that returns a BCR of 4. Climate scenario +3 °C, using the best-bet model to calculate the impact of heat stress for a range of implementation costs and a range of amelioration levels achieved from the research. Lamb price $6/kg.

	Amelioration effectiveness		
Implementation cost	25%	50%	100%
$0	1318	2635	5271
$1	866	2148	4749
$3	305	1375	3853
$5	17	835	3107
$8	0	227	2172
$12	0	0	1220
$15	0	0	592