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A Review on the influence of Climate Change on sheep reproduction

Gregory Sawyer and Edward Jitik Narayan

Abstract

Increasing food and natural fibre production ensure food security for nearly 10 billion people, the projected global population in 2050, without causing further environmental damage can be achieved by transforming systems and adopting sustainable agriculture practices within a changing climate. Globally, climate change effects are having both direct and indirect effects on agricultural productivity including changing rainfall patterns, drought, flooding and the geographical redistribution of pests and diseases. Climate change induced heat stress is thus one of the complex factors making sheep management and husbandry challenging in many geographical locations in the world. Within the sheep industry, reproductive wastage (RW) is a major challenge throughout the varying breeding landscapes. Reproductive wastage is defined as the early losses of embryos undergoing natural and/or artificial breeding programs. Our previous research showed that heat stress ($THI > 75$) and elevated glucocorticoid levels (indexed using faecal glucocorticoid metabolites) are linked to embryo loss in Merino ewes. This mini review discusses how extreme variation in climate such as heat stress affects the maternal reproductive performance in the Merino sheep and the impacts on the wool industry. We provide recommendations to sheep producers for monitoring and managing the effects of heat stress on-farm.

Keywords: reproductive wastage, stress, merino sheep, climate change, resilience, production

1. Introduction

1.1 Interaction between climate, human population and sheep reproduction

As the world's global climate is changing, the United Nations is projecting a global population of nearly 10 billion people by 2050 [1]. It is thus the graziers, farmers and pastoralists who are charged with feeding this population growth, like they have always done since the beginning of time. However, within this changing global climate, domestic animal farmers (sheep, cattle, goats and pigs) will be required to engage with not only the buyers of their products (to show sustainable practices) but also with their environment better by transforming on farm systems through adoption of better sustainable agriculture practices within this changing climate [1].

Globally, climate change has both direct and indirect effects on agricultural productivity including changing rainfall patterns, drought, flooding and the geographical redistribution of pests and diseases [1]. Climate is one of the three

key influences that affect the welfare (health and well-being) of livestock with the others being, nutrition management, external and internal diseases. Synergy among these three key components influences the physiological and phenotypic/behavioural responses of livestock and ultimate productivity.

Recent developments in the field of animal welfare such as non-invasive technology can assess animal emotion and pain and have led to wider interests from researchers and advocate for animal welfare directed research in production animal systems [3], especially in Australia, as a vast and dynamic country which regularly experiences extreme climatic conditions [2].

Livestock animals pioneered into Australia are mostly of the European breed, so they have to cope with the daily challenges presented by the Australian climate, ranging from sub-freezing winters to moderately hot summers. Advancements in the dynamics of Australian agriculture over the past half-century have been channelled mainly through human innovations in machinery, nutrition and animal genetics. These advancements are supplemented with better equipped personalised technologies to predict climatic events [4] including above and below average rainfall or radiant heat loads. However, within Australia, since 1910 the average maximum day time temperature has increased by 0.7°C and a night time temperature increase of 1.1°C, with much of this change occurring since the industrial revolution in the 1950s.

Since the 1940s, small scale research shows that the reproductive potential of Merino ewes may be negatively influenced by one or a combination of environmental factors. In the 1960s and 1970s, key research into heat stress and its influence in RW provided evidence that environmental stress can heavily influence reproductive success in the Merino sheep [5–8]. Previous research into fertility and reproductive ability in mammals also demonstrated, through a wide variety of trials and scientific reviews, the physiological responses associated with the perception or recognition of internal or external stressors [9, 10]. Most recently, Narayan et al. [11] determined that summer heat wave can impact the management outcomes of commercial livestock reproduction programs involved in artificial insemination (AI) and embryo transfer (ET) through the generation of physiological stress and early loss of embryos in ‘hot ewes’ [11]. New research into how climatic induced heat stress represents a physiological challenge to normal expression of life-history traits such as growth, development, behaviour and reproduction in domesticated farm animals is gaining interest throughout the agricultural sector worldwide. In domestic food animals (e.g., Merino ewe and Angus cow), reproductive ability is the most economically important trait that may be compromised by changing environments and subsequent stress [12].

1.2 Current demographics in Australia

Australia is the world’s largest apparel wool growing country (80%), with 100% of all wool produced exported throughout the world. In 2007, the Australian Bureau of Statistics (ABS) reported the total Australian flock numbers of 85.7 million head [13]. The number of breeding ewes (of all breeds) equated to 46.4 million head of the total sheep population in 2007 [14]. The 2017 joint Meat and Livestock Australia (MLA) and Australian Wool Innovation (AWI) quartile report on wool and sheep meat provided sheep numbers, both Merino and other breeds, at vastly reduced levels not seen for generations [16]. According to the ABS (**Table 1**), as of the 30th June 2017 the total Australian flock numbers had reduced to 72.15 million head [17]. The breeding ewe population as of the 30th of June 2017 within Australia was 39.89 million breeding ewes which represent a reduction of 6.51 million breeding ewes aged 1 year and older [19].

| | Number of head |
|---|----------------|
| Breeding ewes 1 year and older [including merinos and all other breeds] | 39,897,000 |
| Lambs under 1 year old | 22,857,000 |
| All other sheep and lambs | 9,371,000 |
| Total sheep in Australia of all breeds and all ages | 72,125,000 |

Source: Australian Bureau of Statistics 2016–2017 End of Financial Year Livestock Numbers (Australian Bureau of Statistics, 2018 [16]).

Table 1.
Australian total sheep population (number of head): as of 30th June 2017.

In 2011, ABS reported a total of 40,000 sheep businesses in Australia only 9814 of which are Merino-based operations [13]. This number had reduced to 31,136 in the ABS 2015–2016 censuses [14].

1.2.1 Wool volume

According to AWI, the volume of all wool tested through the Australian Wool Testing Authority (AWTA) Ltd. has been relatively stable over the past six financial years 2009/2010–2016/2017. During that period the tested volume has been revolving around 360 million kg greasy plus or minus 5% [15].

1.2.2 Sheepmeat volume

Australia is the world’s largest exporter of sheepmeat, and the world’s second largest producer of lamb and mutton [17]. In 2014–2015, the sheepmeat industry accounted for 32% of all farms in Australia with agricultural activity [14]. The off-farm meat value (domestic expenditure plus export value) of the Australian sheepmeat industry was approximately AUD¹ \$4.83 billion in 2015–2016—up 2% on the 2014–2015 periods (MLA estimate).

1.2.3 Climatic and sheep number changes

In the period 1880–2012, the surface global warming was 0.85°C and 2015 was the warmest in the instrumental record [18]. Heatwaves in 2013 (Australia’s hottest year), 2014 and 2015 had substantial impacts on infrastructure, health, electricity supply, transport and agriculture [18]. When we compare this climate change increase in heating of the Australian land and sea environments between 2012 and 2016, 32 of the 39 geographical areas, as determined by Meat and Livestock Australia, had decreases in sheep populations up to 41% of the 2011 total. Appendix 1 provides information on sheep population change between 2012–2013 and 2015–2016 financial years as provided by Meat and Livestock Australia [19].

2. Climate change

Climate change is defined as the long-term misbalance of customary weather conditions such as temperature, wind and rainfall characteristics of a specific

¹ AUD-Australian Dollar Value

region and it is likely to be one of the main challenges that mankind faces during the present century [20]. Climatic change impacts on agriculture and livestock are being witnessed all around the world [21, 24, 25]. The United Nations Food and Agriculture Organisation [59] in 2008 recognised that throughout the world, there is increasing general agreement that the direct effects of climate change will be of a similar nature in both low and high-external input livestock production systems.

The Earth's climate is predicted to continually change at rates unprecedented in recent human history [20, 22]. Current climate models indicate a 0.28°C temperature increase per decade for the next two decades and predict the increase in global average surface temperature by 2100 may be between 1.88 and 4.08°C [20, 22]. According to NASA [23], the global average surface temperature increased from 0.6 to 0.9°C between 1906 and 2005, and the *rate* of temperature increase has nearly doubled in the last 50 years. The Earth's climate has warmed dramatically in the last century, with the 1990s and 2000s being the warmest on instrumental record [20, 22]. A selection of global climate models projects the average Australian temperature relative to 1990 to increase by 0.1–1.3°C by 2020, 0.3–3.4°C by 2050 and up to 6.7°C by 2080 [26].

3. Climate change and thermal stress

Within an animal breeding environment, ambient temperature is a most important variable as its effect is aggravated in the presence of high humidity [27]. Concerningly, as temperature and humidity levels increase over much of the continent [28] amplified thermal stress on animals is expected. Thermal (heat) stress is defined as any combination of environmental parameters producing conditions that are higher than the temperature range of the animal's thermoneutral zone (TNZ) [30]. Thermal stress can adversely affect a range of reproduction indices, including a suppressive effect on reproductive hormones [31].

Pregnant and lactating ruminants are more susceptible to heat stress than non-pregnant and non-lactating individuals [32, 33, 53]. As the animal is affected by heat stress, via HPA activation the animal reduces its reproduction role within both the male (sperm mobility, sperm abnormalities) and in the female (through reduced oestrous activity, embryonic mortality) [33]. Physiologically, the metabolic changes within the animal due to the influence of heat stress can be assessed in a sheep through non-invasive assessment methods. Chronic stress can be measured in raw wool samples as well as progesterone to determine pregnancy in stressed and non-stressed sheep [29]. Those ewes which are affected by heat stress and heat shock acutely can have through non-invasive methods have faecal matter tested for stress [29].

In cattle, Dash [34] showed a negative correlation between reproduction traits, temperature humidity index (THI) with animals experiencing adverse effects of heat stress when the THI crosses a threshold level greater than 75.

Due to the size of Australia and the location of the Australian sheep breeding areas (tablelands, grasslands, rangelands, arid) various physical environmental stressors (PES) are dynamic and can be localised or decentralised within the greater region. PES include: high ambient temperature, high direct and indirect solar radiation, wind speed, and relative humidity. Among the physical environmental stressors, ambient temperature is ecologically the most important [47]. PES can cause the effective temperature of the environment to often exceed the TNZ of the animals [43], leading to heat stress [44–46].

In sheep, Narayan et al. [11] showed that heat stress reduces embryo production during AI/ET because the physiological and cellular aspects of reproductive function and early embryo development are disrupted. Thus, climatic change induced heat stress can diminish reproductive capacity in the Merino ewe due to an increase in body temperature as it is exposed to elevated ambient temperature, and by the physiological adaptations of cells coping with thermal stress [35, 36].

In Merino sheep, elevated maternal cortisol levels caused by thermal stress can lead to a programming of the hypothalamic-pituitary-adrenal (HPA) axis. It has emerged that this HPA axis programming is a possible key mechanism [37, 38] resulting in the foetal adaptation to its environment; the placenta acts as a connection between the mother and the developing foetus and stress activates maternal HPA axis functioning and triggers glucocorticoid (GC) secretion that reaches the foetus by transplacental passage [39]. Glover's [39] research confers that behaviours and health outcomes in an offspring may result from long-lasting endocrine changes between the maternal-foetal nexus guided by complex networks of hormones (e.g., glucocorticoids, insulin-like growth factors-IGFs and hormones expressed along the brain-gut axis) [39]. With sheep breeding enterprises impact of climate change that causes GC secretion may induce epigenetic changes within individual animals among larger sheep populations—the effect of which will have long lasting changes to the DNA of future disease resistance, reproduction capacity and nutritional conversions in the future off spring(s) [89].

Heat stress is qualified as cytotoxic, as it alters biological molecules, disturbs cell functions, modulates metabolic reactions, induces oxidative cell damage and activates both apoptosis and necrosis pathways [33, 40]. Epigenetic modifications can also occur in the offspring of pregnant ewes in response to external or internal environmental factors (i.e., heat stress and water stress). Heat stress is thus one of the complex factors making sheep management and husbandry challenging in many geographical locations in the world [42, 98].

3.1 Climate change and sheep welfare

Climatic change that causes chronic heat stress is considered the most important external factor drastically affecting long term small ruminant (sheep) reproduction globally [21, 51, 52]. Since domestication, sheep have established a wide geographical range due to their adaptability to nutrient-rich and nutrient-poor diets, along with tolerance to extreme climatic conditions [41].

Australian vast land mass and varying weather and changing climatic challenges are dominant features. Thus, Australian sheep of all breeds are exposed to not only a progressively warming climate, but, superimposed on that, to more frequent and extreme heat waves and droughts [48]. As a result, a warming climate that accompanies both a nutrition and water shortage is likely to present a severe challenge to a sheep homeostasis during periods of prolonged droughts.

As the environment imposes a heat load on sheep, which it will do increasingly as air temperatures rise, the only way for sheep to lose that heat and their metabolic heat is through evaporative cooling [49]. This mechanism is particularly important for sheep exposed to solar radiation. The cooling mechanism of thermoregulation in sheep will be challenged as they are small ruminants and homeotherms, so they must regulate their body temperature within a narrow range (38.5–39.5°C) to remain healthy and productive.

Thermoregulation is crucial to mammalian climate change resilience. Those sheep that are not suited or acclimatised via thermoregulation to thermal stress caused by heating of environmental conditions can result in significant elevation

in body temperature which influences ovarian function, oestrus expression, oocyte health and embryonic development [34].

Within these challenges driven by the climatic change, sheep producers should anticipate changes in preimplantation environmental conditions (1), the uterine and placental competency (2), and adequate nutrient transport across the placenta (3), all of which are stressors that can all alter foetal development trajectories [50]. Alliston and Ulberg [54], Sawyer [7] and recently Narayan et al. [11] provided concise evidence that ewes subject to high air temperature at time of mating will have a reduced reproductive rate through embryo loss [8, 11, 54]. Thermal stress is also known to influence the superovulation response in sheep [55] and cattle [56, 57] in a multiple ovulation and embryo transfer program (MOET) [58].

Due to climate change, the frequency of catastrophic events (drought, flood, ambient temperature decrease, and increase), as well as possible disease epidemics and water scarcity, there is an increase in physiological stress, reduced productivity and genetic losses [59]. How well sheep are able to buffer the effects of climate change [48] will directly affect reproductive fitness, through the effects of heat stress on physiological tolerance, performance and reproductive capacity. Therefore, within the various Australian sheep breeding climates, the Australian Merino ewe will be affected by increased climatic stress experienced in either winter or summer, as seasonal conditions change with climate change.

3.2 Adaptation to thermal stress

Evidence suggests that differences exist between domesticated ruminant species, breed and production level that will influence heat stress susceptibility [60, 61] and subsequent heat stress adaptation. This is mainly due to species' differences in the ability to reduce metabolic and endogenous heat production and increase heat dissipation. For instance, animals adapted to hot environments have lower metabolic and water turnover rates, and a higher capacity to dissipate heat via panting and sweating [62]. Among species, sheep and goats are considered less sensitive to heat stress than cattle [60, 63].

There is evidence for a temporal biphasic pattern of heat acclimation: short-term and long-term heat acclimations (STHA and LTHA, respectively) [64–66]. STHA is the phase in which changes are initiated within cellular signalling pathways [64] leading to disturbances in cellular homeostasis that begins to reprogram cells to survive the deleterious effects of heat stress [66]. In rodents, the full expression of STHA is attained when the plasmatic thyroid hormones (T3 and T4) levels exceeds 30–40% [66].

In ruminants, the STHA is characterised by responses initiated to compensate for the increased heat stress before permanent acclimation can be obtained. Increased heat dissipation (primarily through evaporative heat loss), reduces feed intake. Milk yield, increased water intake and tender wool in woollen sheep breeds are examples of the STHA response [52]. Within various long-term and short-term climate change projections, research continually show that biophysical events directly impact on livestock affecting nutrition requirements and reproductive success [20].

Wool is a natural indicator of short-term stress exposure within the sheep's natural environment. Wool fibres reduce in microns at the point of stress caused by individual events or through a combination of factors (nutrition, disease or pregnancy) (**Figure 1**). As the animal grows the wool throughout the wool growing period (normally 12 months), visual assessment along, within wool testing laboratory that can determine key stress periods in animals that have experienced STHA. However, LTHA exposure to nutritional stress along the full wool growth period will not see



Figure 1.
An example of tender fleece and the occurrence of a fleece break. Source: Approval from Ooranoork pastoral company private photo collection 2018.

the wool break as the animal is on a constant plane of nutrition. The fibre may still break however if the animal develops STHA disease or pregnancy stress while being nutritionally challenged.

When the initial acclimation phase is complete, and the heat-acclimated phenotype is expressed, LTHA occurs [47, 66]. LTHA is characterised by a reprogrammed gene expression and cellular response resulting in enhanced efficiency of signalling pathways and metabolic processes [47], and this, in large part, may be mediated by heat shock proteins (HSP) [67].

The phase of acclimation is also characterised by endocrine changes presumably with the goal of decreasing metabolic heat production and increasing heat dissipation. An example of LTHA is an ewe's body temperature that is chronically (for 40–45 days) heat-stressed ($\text{THI} = 82$), presenting similar results as those reported for heifers [20, 68] and cows [20, 68] In cattle, heat stress has also been associated with impaired embryo development and increased embryo mortality [35, 36, 83] see **Figure 2** for ewe effect to heat stress.

Mittal and Ghosh [69] provide key research that shows animals that can maintain or adjust physiological responses within normal limits under stressful environmental conditions may be considered adapted to that environment and hence worth rearing commercially [58, 69]. This research, when used alongside current maternal nutrition research [70, 71], suggests that animals have a prenatal growth trajectory which is sensitive to both direct and indirect effects of both maternal nutrition and stressful environmental conditions at all stages between oocyte maturation and birth [71, 72].

The biological mechanism by which heat stress impacts animal production and reproduction is partly explained by reduced feed intake. However, it also includes an altered endocrine status, reduction in rumination and nutrient absorption, and increased maintenance requirements [61] resulting in a net decrease in nutrient/energy availability. Naturally, a reduction in energy intake, combined with increased energy expenditure for maintenance, lowers the energy balance, and

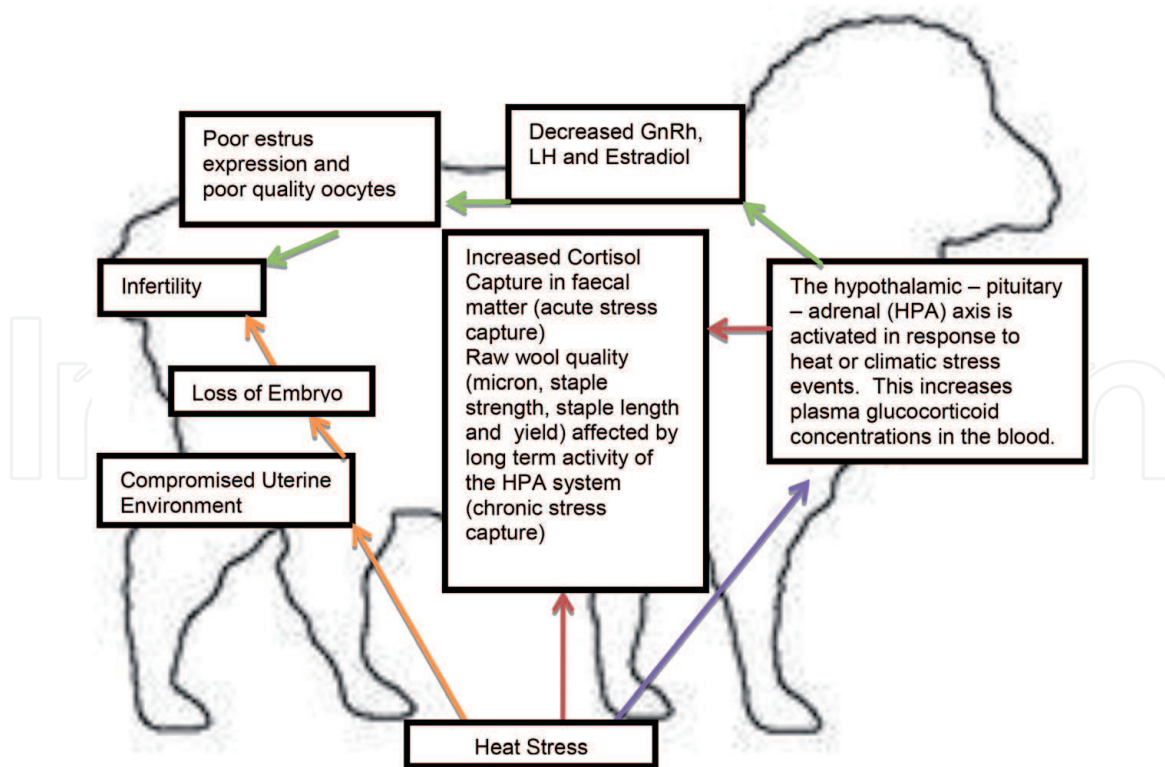


Figure 2.

Climate change induced heat stress effect on the Ovis aries: increased cortisol capture in faecal (STHA) and wool (LTHA), HPA axis activates, decreased hormones, poor estrus and lower quality oocytes, compromised uterine environment, loss of embryo leading to infertility.

partially explains why lactating cattle lose a significant amount of body weight during severe heat stress [20, 72, 73]. Reduction in energy intake coupled with increased maintenance costs during heat stress causes negative energy balance (NEBAL) in lactating cows (likely stage of lactation independent) and a bioenergetic state, similar (but not into the same extent) to the NEBAL observed in early lactation. The NEBAL associated with the early post-partum period is coupled with increased risk of metabolic disorders and health problems, decreased milk yield and reduced reproductive performance [20, 74]. Similarly, we hypothesise that many of the negative effects of heat stress on Merino production, health and reproduction indices might be mediated by NEBAL.

However, in ewes, as with cows, further research is required to know how much of the reduction in performance (yield and reproduction) can be attributed or accounted directly (hyperthermia) or indirectly (reduced feed intake) to heat stress [20]. Heat stress acclimation is accomplished by changes in homeostatic responses [47] and may include homeorhetic/teleophoretic processes involving an altered endocrine status that ultimately affects target tissue responsiveness to environmental stimuli. Initial responses are considered for homeostatic mechanisms and these include increased water intake, sweating and respiration rates, reduced heart rate and feed intake [47, 75]. Hormones are also implicated in the acclimatory response to heat stress [61] and they primarily include thyroid hormones, prolactin, GH, glucocorticoids and mineral corticoids.

Furthermore, protein synthesis as well as deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) polymerisation is disrupted under heat stress. Whereas protein and RNA synthesis recover rapidly after heat exposure, DNA synthesis remains inhibited for a longer period [76, 77]. Further, heat stress is responsible of protein denaturation, and also induces their aggregation into the nuclear matrix. This aggregation increases the nuclear protein concentration [76, 77]. Therefore, many

molecular functions are altered, such as DNA synthesis, replication and repair, cellular division and nuclear enzymes and DNA polymerases functions [78]. Further research is required on how heat induced stress can lead to epigenetic change in the DNA of offspring and subsequent phenotype.

Accurately identifying heat-stressed ruminants and understanding the biological mechanism(s) by which thermal stress reduces reproductive indices, milk synthesis and growth, is critical for developing novel stock management approaches (i.e., genetic, managerial and nutritional). This is particularly important for Australian Merino sheep producers, to understand as it influences production traits and reproduction capacity, especially during periods of thermal (heat) stress.

4. Reproductive wastage

Lamb marking percentages in Australia have changed little for many generations [79, 80], despite improvements in breeding, nutrition and tools for managing pregnant ewes [80, 81]. The wider influence and effects of climate change on lamb marking percentages is yet to be researched. However, climate induced heat stress during pregnancy is known to slow down foetal growth and increase foetal loss [20]. Even in favourable seasons, across a range of different sheep enterprises, lamb losses in order of 10–30% for single and twin bearing ewes, respectively, are to be expected [82]. In lead in years to the 2018 drought in New South Wales and Queensland, many regions experienced very little rain fall, cold dry winters, hot summers and vastly lowered nutritional benefit from grazing productive pastures resulting in many sheep graziers having reproductive wastage (RW) in excess of 60% in their sheep populations.

Within Australia, Merino lives and reproduces in complex macro (tropical, temperate, arid) and micro environments in which they are constantly confronted with short- and long-term environmental changes caused by a wide range of factors [27]. Embryo development within the micro-environment formed by the oviduct and uterus is influenced by the outside environment [35, 36]. If a moderate climatic change causes an increase in temperature beyond the TNZ of the maternal ewe, the cellular environment surrounding the embryo, and needed for development and growth, can be impacted. Thus, the body temperature of Merino female around the time of mating is vital for reproductive success.

Within various ruminants like sheep there are genetic differences with respect to heat stress adaptations and these may provide clues or tools to select productive and thermotolerant animals. These differences include the role of Heat Shock Proteins (HSP) in coordinating thermotolerance, the quality of the ova, the incidence of oestrus and the asynchrony between conceptus and uterus at implantation. The association between polymorphisms within the HSP genes suggests a better understanding of these relationships would help identify positive production traits and factors that impact physiological response to heat stress.

The magnitude of either one of the three key influences that affect the welfare (health and well-being) of livestock, these being climate, nutrition management and external and internal diseases, can impact oocyte quality and thereby influence fertility [84]. The quality of the oocyte is a crucial component in determining reproduction wastage. Oocyte and/or embryo quality is most affected when ewes are exposed to a hot environment during the first 3 days after artificial insemination [8]. High internal body temperature > 39.5°C leads to high cortisol (stress) levels and subsequently reduced levels of transferable eggs in AI/ET [11].

In previous research, Lindsay et al. [85] found no significant relationship between mean maximum temperature and the incidence of oestrus for Merino flocks in Western Australia [85]. However, in the same study the authors identified a negative correlation between the ambient temperature and lambing performance, but only when a higher temperature coincided with the time of mating or the few weeks thereafter. Within the South Australia environment, Kleemann and Walker [86] observed a significant decline (97–87%) in fertility as mean maximum temperatures increased $<32^{\circ}\text{C}$ over three or more days [86]. They concluded that the reductions in lambing performance were due to increases in embryo mortality (a direct indicator of reproductive wastage). Dutt [5, 9] and Thwaites [7] in the 1960s and 1970s concluded that increasing environmental ambient temperatures within 8 days prior to conception, as well as high post-mating temperatures (within 2–3 weeks post joining), had also significantly reduced embryo survival rates. Narayan et al. [11], expanding on this earlier research, found that acute heat stress, elevated rectal temperature and elevated cortisol could adversely affect the fertility of Merino ewes.

A complication affecting the reproductive capacity in ewes is the asynchrony between conceptus and uterus at implantation [87] with as many as one-fourth of all successful fertilizations not result in a viable pregnancy, even in the absence of environmental stressors [88].

4.1 Nutritional affect

The connection between nutrition and the outcomes of reproduction in sheep extensively researched for over 50 years in Australian sheep [4–7, 18, 19, 29, 30, 45, 55, 65, 67, 77, 78, 90]. A major key determinant of the reproductive success in ewes is the relation between their live body weight (BW) and their body shape and her body condition score (BCS). Both BW and BCS (in a five-point score where 1 BCS is very low to BCS 5 is very fat: 3 BCS is ideal for joining) have a direct relationship with nutrition and water quality from pre joining, post joining and post lambing periods. If the ewe has access to continual low-quality nutrition throughout pre and post pregnancy, her reserves of body fat will be metabolised to assist with supporting herself and her unborn or recently born lamb. Previous research by Ferguson et al. [70] noted that the nutritional requirements of the ewe can be difficult to predict due to the difference in the ewe and unborn lambs' energy requirements. Ferguson et al. [70] determined that nutritional intake capacity was influenced by the point of pregnancy and lactation and the number of lambs born and reared.

Researchers of this paper have observed hundreds of thousands of ewe(s) of various breeds within different climate zones in Australia since 1987–2019. It was noticeable that ewes with low BCS had low metabolised fat reserves, thus it appeared and could be determined that the ewe was under greater nutritional stress (especially caused through climatic events such as drought or floods). Individual ewe management is important with ewes with very low BCS (1–2.25 points) during pregnancy required to be given alternative feed to lift convertible nutrition outcomes. This is particularly important, as researchers and farmers have observed in paddock scenarios the ewe putting her survival before her embryos and aborting the unborn lamb. If the lamb is newly born (usually within 7 days), it is not uncommon for the ewe to walk away from the lamb so that she can survive. This is mostly seen in low and very low BCS ewes who have subsequent reduced nutritional energy, poor lactation and may have been affected by climatic nutritional stress (in particular drought and flood events).

As BW and BCS can significantly influence the fertility and fecundity of breeding ewes [70, 91–93], Borg et al. [94] estimated positive correlations between the number of lambs born and maternal body weight change during late gestation which could be achieved with various on farm management practices including

shearing patterns and feeding regimes [94]. This seems to further support the postulation that epigenetic factors such as nutrition and climatic factors can influence the maternal environment and influence the outcome of conception with either successful breeding or embryo/lamb loss.

4.2 Heat stress and reproductive wastage

Previous research by Dutt [5, 9], Thwaites [7], Sawyer [8], Naqvi et al. [58], and Narayan et al. [11] provide evidence that ewes which are subjected to high air temperature ($<32^{\circ}\text{C}$) at time of mating will have a reduced reproductive rate due to an increased embryonic death rate. Ewes selected on the basis of their tolerance to heat stress indicate that the group selected for lower rectal temperature had higher joining (89% vs. 63%) and lamb marking rates (82% vs. 50%) than those selected for high rectal temperature $\geq 39.9^{\circ}\text{C}$ [95].

The inability of the animal to manage any combination of environmental conditions (i.e., air temperature, relative humidity, solar radiation) above the ewe's TNZ [41] is a prime cause of heat stress and RW. Given the rate of climate change and the near-term acceleration in the rate of temperature change within ecologically critical terrestrial climate conditions, many animals alive now will experience biologically significant climate change within their expected lifetimes [48].

While there are several possible mechanisms by which heat stress can prevent the growth of oocytes, the primary response, as determined in cattle and shown by Dash [34], is the reduction on the synthesis of preovulatory surge in the luteinizing hormone and estradiol [34]. Dash's research [34], followed by Hansen's work [35, 36], showed that due to heat stress, there was also poor follicle maturation and this leads to ovarian inactivity in cattle [34–36]. Khodaei-Motlagh [96], by determining reproductive hormones in dairy cattle in 2011, showed that heat stress delays follicle selection and reduces the degree of dominance of the dominant follicle [96]. This echoes an earlier study in 2003 that indicated heat stress may reduce summer fertility in dairy and beef cattle by causing poor estrous expression due to reduced estradiol secretion from the dominant follicle developing in a low luteinizing hormone environment [101], and that the dominant follicle is susceptible to heat stress [100]. The reason for the delay to onset of estrus could be due to a modified pulsatile release of LH and a decrease in oestrogen secretion. The normal GnRH release patterns (and subsequent frequency and amplitude of LH pulses secreted from the pituitary) are reduced by exposure to thermal stress [99]. This lack of function due to climatic pressures of heat and humidity can result in abnormal ovarian functions and hence cause a delay in the LH surge [58].

In evolutionary terms, when fertility of an individual ewe's is reduced by heat stress, the dominance of the selected follicle is reduced in consequence of a reduction of the steroidogenic capacity of theca and granulosa cells driving a fall in blood estradiol concentrations [101]. It is also widely accepted that heat stress induces a percentage of infertility in animals not suited or acclimatised internally to thermal stress. As with all homeotherms, the Merino ewe has the ability to rid itself of this sub-vital energy drain (i.e., pregnancy) due to the additional stress caused by the extreme climate which becomes a trade-off for immediate health and survival [87].

5. Final considerations

In varying sheep breeding regions, producers are likely to see a substantial increase in the frequency of heat stress days above their normal climatic conditions that may result in reduced productivity and decreased reproductive rates [102].

The ewe is the driving force of the wool and sheep meat industry, both locally and globally, as it provides both Merino and cross bred lambs and furthermore, passes valuable genetics on to the next generation [11]. In sheep reproduction and endocrinology there is now an increasingly urgent industry desire and need for further research on the physiological changes in ewes caused by climate change.

As sheep are small ruminants and homeotherms they must regulate their body temperature within a narrow range to remain healthy and productive. Heat stress is thus considered the most important factor affecting small ruminant production under changing climatic conditions [21, 51, 52]. When the physiological mechanisms in ruminants/sheep fail to alleviate the effect of heat load due to climatic changes in the environment, the body's high temperature may increase to a point at which animal well-being and reproductive capacity is compromised [5–11].

Due to the various combinations of factors such as temperature, humidity, wind and direct and indirect radiations [20] various stressors (heat cold, nutritional, disease) will be an ever-present feature of life for sheep farmers. Along with epigenetic (non-genomic) patterns resulting in altered embryo and neonate survival rates [97] the effects of climate change are one of the three key influences that affect the welfare (health and well-being) of sheep, and all livestock, with the others being nutrition management and external and internal diseases. These three key influences may cause STHA or LTHA stressors and their interaction is likely to add to and exacerbate existing pastoral grazing management challenges to sheep producers that compromise animal nutrition and health [101, 102] and subsequently reduce reproductive performance.

This review then confirms earlier research by Thwaites [7], Sawyer [8], Dutt [5, 9] and Narayan [11] that exposure of ewes to high ambient temperatures at various stages of the reproductive cycle has a detrimental effect on fertilisation rate and embryo survival. Therefore, with an increase in ambient temperatures due to climate change we hypothesis that as the climate continues to warm, the fertility of ewes will be compromised without individual management technology assessment, that is, individual health monitor located in an ear tag.

New research would provide a greater understanding of how the current sheep breed performance is challenged by the thermal environment and how on-farm practices could be improved through the application of innovative tools to assess animal welfare. Such research would help to optimise technology for making on-farm data collection (e.g., reproductive cycles) available more easily and in-real time (e.g., through applications of digital ear-tag technologies). It is acknowledged that for further growth and prosperity into the future, the sheep industry needs to proactively develop out of square thinking and innovative approaches to meet the challenge of climatic change. This would help promote positive growth into the future of the global sheep industries and wider livestock industry.

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