Breeding Focus 2021 - Improving Reproduction

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Published by

Animal Genetics and Breeding Unit

University of New England

Armidale, NSW, Australia

Animal Genetics and Breeding Unit

University of New England

Armidale NSW 2351

Australia

http://agbu.une.edu.au

ISBN: 978-1-921597-86-2

e**ISBN**: 978-1-921597-87-9

Cover design by Susan Joyal

Book design by Kathy Dobos

First published, 2021

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Preface

"Breeding Focus 2021 – Improving reproduction" is the fourth workshop in the series. The Breeding Focus series was developed to provide an opportunity for exchange between industry and research across a number of agricultural industry sectors. With this goal in mind, workshops have included presentations across multiple agriculturally relevant animal species to take participants outside their area of expertise and encourage them to think outside the box. Reproduction is a main driver for profitability and genetic gain. We will discuss existing knowledge, identify gaps and explore genetic and management strategies to improve reproduction further in multiple species.

Successful reproduction is a complex characteristic comprising the formation of reproductive cells, successful mating and fertilisation, embryonic and fetal growth and eventually a successful birthing event. In livestock species, reproduction traits have mostly low heritabilities, which makes it challenging to improve reproduction as part of a multiple trait breeding objective. The complexity arises not just from the cascade of processes required to result in successful reproduction, but the relevant traits are different in males and females and they are influenced through health and fitness, nutrition, climate and other environmental and management factors.

Challenges to the improvement of reproduction can vary widely for different species. For less domesticated species such as abalone, the ability to produce and reproduce the animals in captivity presents a major challenge. In bees, reproduction has not been given great attention and little research has been undertaken to understand the underlying genetics of drone and queen reproduction. However, in all industries reproduction is recognised as the basis for genetic and economic gain. It directly influences the selection intensity that can be applied. It also determines how many animals are not required for replacement and can be sold. In all industries, irrespective of the challenge, cost-effective and easy to measure phenotypes of reasonable heritability are central. New technologies and approaches enable the development of novel phenotypes for genetic improvement which will be combined with a growing amount of genomic data in livestock species and together these developments provide new and exciting opportunities to improve reproduction further.

We would like to thank everyone who has contributed to this event for their time and effort: the authors for their contributions to the book and presentations, the reviewers who all readily agreed to critique the manuscripts. We would like to express a special thanks to Kathy Dobos for her contributions into the organisation of this workshop and the publication. Thank you!

Susanne Hermesch and Sonja Dominik

Armidale, May 2021

Lamb survival, a challenge for the decades

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Abstract

Lamb survival to weaning is the major profit driver in the Australian sheep industry, and equally an important issue for animal welfare and ethical livestock production. Research aimed at improving lamb survival and reproductive efficiency remains consistently one of the highest-ranking priorities identified by industry consultation groups. The extensive body of knowledge generated by research efforts across Australia have led to comprehensive management guidelines and extension programs to support their uptake. Nevertheless, reported rates of loss in many regions remains higher than acceptable, despite lamb loss rates in general improving under improved management strategies. One of the biggest challenges is to break down this complex phenotype into measurable meaningful component traits. As for any complex phenotype, a combination of improved management and genetic selection may be most likely to lead to success but for either application, phenotypes must be less dependent on uncontrollable environmental influences than counts of losses. Dystocia has been conclusively shown to be one of the most important causes of lamb loss and development of approaches to measure incidence of dystocia will aid the development of new phenotypes to facilitate genetic and management strategies to improve lamb survival.

An old problem calling for new solutions

Neonatal lamb mortality is the single largest economic and welfare driver for the Australian Sheep industry (Lane 2015), with the cost recently estimated to range between $700M to $1B depending on prevailing sheep and lamb values (Young *et al.* 2014; Kubeil 2017). Lamb weaning rate is one of the main determinants of profitability of sheep enterprises, and neonatal mortality is the predominant stage of lamb loss up to weaning (Hinch and Brien 2014). Aside from the direct economic cost of producing fewer animals for production or sale, lamb mortality also incurs an indirect cost through reducing animals available for selection, impacting the rate of genetic gain. Beyond productivity losses, there are also ethics and animal welfare implications, with additional impacts on the mental health of farmers, social licence, and the sustainability of the industry.

Neonatal lamb mortality and its impact on reproductive performance in Australia has been reviewed previously (Kleeman and Walker 2005; Fowler 2007; Hinch and Brien 2014). According to Hinch and Brien (2014) there has been little, if any improvement in weaning rates or lamb survival in Australia since the 1950s. Averaged across sheep breeds and types, environments, production systems and years, mortality rates among single-born lambs usually ranged from 15-25% and 30-50% for twin-born lambs. Recent Meat and Livestock Australia (MLA) and Australian Wool Innovation wool and lamb producer surveys which report lamb marking rates indicate current lamb mortality rates appear similar to historical levels (MLA 2020). In this review, we are considering where opportunities lie to develop new phenotypes associated with, and relevant for, lamb survival, which may allow stronger focus on the perinatal physiological state of ewe and lamb and stronger separation from environmental factors.

Kubeil (2017) reported that although lamb marking rates in Australia increased by approximately 13% in the period between 2006 and 2016, that improvement has not arisen from an improvement in lamb survival. This increase was attributed to a shift in the ewe base from purebred Merino ewes toward cross-bred ewes that have higher fecundity. It was suggested that the lack of progress in improving lamb survival is attributable to a) poor acknowledgement of the scale of the problem (underestimation of lamb losses by growers) and b) poor adoption of management practices aimed at minimising lamb losses such as optimised breeding ewe nutrition and management of body condition, pregnancy scanning for litter size, differential management of ewes based on litter size, and selection, setup and stocking rate in lambing paddocks.

Allworth *et al.* (2017) surveyed sheep breeders in south-eastern Australia who had adopted best practice methods for lambing ewe management. Those producers still experienced lamb mortality rates toward the lower end of the historical averages reported by Hinch and Brien (2014; 11% singles, 29% twins). This suggests that more than simply improving adoption of best management practices is required to improve lamb survival rates. This may include genetic improvement of traits of the ewe and/or the lamb.

Genetic selection for increased lamb survival was first investigated by George Alexander who conducted research in the area on the CSIRO research property at Chiswick in the Northern tablelands of New South Wales (NSW) in the 1960s. Alexander established a productive research program on neonatal metabolism, ewe-lamb behaviour and causes of neonatal lamb mortality (Alexander 1961; Alexander and Williams 1968; Alexander *et al.* 1993), also summarised by Bell (2018). One study by Alexander *et al.* (1983) suggested that Merino ewes are less capable than other breeds of maintaining contact with and keeping twin lambs together in the 24 hours following birth. These views are still supported by a recent survey of sheep breeders in southern NSW by Allworth *et al*. (2017). In general, the producers surveyed were operating to good industry practices such as pregnancy scanning, preferential feeding of twin-bearers, and preparation of lambing paddocks, and reported an average lamb mortality to marking of 21% for Merinos and 13% for Merino crosses and other breeds. Breed differences point to underlying genetic mechanisms; however, progress in achieving genetic improvement in lamb survival has been limited.

Traits associated with lamb survival have low heritability. If lamb survival is treated as a trait of the ewe, heritability is higher than when treated as a trait of the lamb (Brien *et al.* 2011). Lamb survival of singles appears to be regulated by different mechanisms to that of multiples and Kelly *et al.* (2016) conclude that lamb survival should be considered as separate genetic traits across different birth types. Bunter *et al.* (2018) determined that litter size at lambing influences genetic evaluation of maternal rearing ability. Development of genetic traits for maternal behaviour has been suggested as a possibility of improving lamb survival for non-Merino breeds in New Zealand (Everett-Hincks and Cullen 2009). In Scottish Blackface sheep, a breed renowned for high rearing ability, Maternal Behaviour Score (MBS) showed low heritability (h^2=0.13; Lambe *et al.* (2001)). In this study, ewes with very poor MBS lost more lambs than higher-scoring ewes and selection to reduce ewes in this category was suggested as potentially strategy. In contrast, a study examining the potential to use temperament traits in Merino ewes for improvement of lamb survival found ewe mothering temperament moderately heritable (h^2=0.35) and it had a low positive genetic correlation with litter survival (rg = 0.18; Plush *et al.* (2011)). Selection for more readily measurable temperament traits such as agitation score or flight time appeared even less promising in the same study. In fact, selection for temperament in experimental selection lines has so far not been successful in improving maternal behaviour or reproductive success (Bickell *et al.* 2009; Bickell *et al.* 2010).

Causes of lamb mortality

The majority of lamb death occurs at birth or within 3-7 days of birth. Causes of neonatal mortality in Australian flocks were most recently reviewed by Hinch and Brien (2014) and Jacobson *et al.* (2020). The most recent large-scale study of causes of neonatal mortality was based on the Sheep Industry Cooperative Research Centre (Sheep CRC) Information Nucleus Flock (INF) (Refshauge *et al.* 2016). Across the literature it is generally acknowledged that dystocia (birth difficulty) and starvation are the two major causes of neonatal mortality in Australian sheep flocks (Hinch and Brien 2014).

Without autopsy, deaths attributable to birth injury can be easily mistaken for starvation (Haughey 1973a), and those from either birth injury or starvation can be mistaken for primary predation (Rowley 1970). Further, there are often several contributing, interacting or predisposing factors to a death, particularly those that involve birth injury, starvation, exposure, mismothering, abandonment and predation. Therefore, the underlying cause of death is not always clear from external evidence (Hinch and Brien 2014). This implies that in industry, where autopsy of dead lambs is not routine, misdiagnosis of neonatal mortality would be commonplace. Holst (2004) recommended that to determine the predominant causes of lamb deaths, autopsies need to be conducted on all lambs and for the full duration of the lambing period.

Hinch and Brien (2014) summarised studies conducted in Australia reporting cause of death data from autopsy of dead neonatal lambs, with reported rates of loss ranging between 6 and 31% for single-born lambs, and between 19 and 63% for twin-born lambs. Since then, Refshauge *et al*. (2016) have reported on neonatal mortality in the Sheep CRC INF. An earlier conducted by Holst *et al.* (2002) reported data from various crosses of Merino, maternal and terminal breeds. In addition, four large-scale studies based on Merinos ewes have been reported, two in NSW and one each in QLD and WA (Table 1). Comparison of these studies is difficult for various reasons, but in general, they are divided between those that identified starvation as the predominant cause of death (48%, 58% and 72% from Dennis (1974), Luff (1980) and Smith (1964) respectively), and those that identified dystocia as the predominant cause of death (54%, 67% and 48% from Hughes *et al.* (1964), Holst *et al*. (2002) and Refshauge *et al*. (2016) respectively). The ongoing Merino Lifetime Productivity Project (AMSEA 2021) will provide an important insight into reproductive outcomes of contemporary Merino ewes although it does not routinely include lamb autopsies.

Table 1. Overview of key Australian studies using autopsies to diagnose cause of neonatal mortality

Location and study design	Lambs autopsied (n)	% Neonatal mortality					
		All dystocia	**Primary dystocia**	**Stillborn**	**Birth injury**	**Starvation/ Exposure**	**Other[1]**
Sheep CRC INF, 8 locations across Australia, over 4 years, many sire breeds, 2 dam breeds (Merino and XB)[2]	3198	**48**	9	21	18	30	22
NSW DPI, Cowra, over 3 years, 6 sire breeds, 2 dam breeds (Merino and XB)[3]	700	**67**	20	8	39	21	12
NSW Riverina, commercial Merino flocks[4]	2534	18				**58**	24
WA, 695 commercial properties, over 3 years, predominantly Merino[5]	4417	19				**48**	33
NSW central/ southern Tablelands, 120 properties, over 3 years, Merino[6]	3503	**54**				15	31
QLD central west, 5 mobs over 4 years, Merino[7]	981	13	12	1		**72**	15

[2]Refshauge *et al*. (2016); [3]Holst *et al* .(2002); [4]Luff (1980), cited in Hinch *et al*. (2014); [5]Dennis (1974); [6]Hughes *et al*. (1964); [7]Smith (1964); XB = crossbred

Refshauge *et al*. (2016) and Holst *et al*. (2002) comprehensively subdivided dystocia into the 3 categories of primary dystocia, stillbirth and birth injury, which were defined by Holst (2004). A key characteristic of the method described by Holst (2004) is the definition and categorisation of types of dystocia and the separation of birth injury from starvation based on the degree of cranial and spinal cord haemorrhage assessed on a 1-5 scale, and whether or not there was kidney fat metabolism.

Older studies did not classify different subgroups of dystocia, and hence at least a proportion of the deaths classified as 'Starvation/Exposure' may have been late effects of undetected birth injury, and hence the underlying causation would have potentially been attributable to dystocia.

Understanding dystocia

Historically, dystocia (birth difficulty) has been regarded to be the result of either malpresentation or foeto-pelvic disproportion, both of which cause the lamb to die either during birth or in the hours following birth (Haughey 1983). Jacobson *et al*. (2020) have reviewed dystocia and describe it in terms of maternal and foetal forms. In this categorisation, maternal dystocia arises from foetopelvic disproportion, uterine inertia or various types of obstruction, including failure of cervix dilation, vaginal prolapse, uterine torsion and inguinal hernia. In comparison foetal dystocia is due to malpresentation, foetal disease or death, and congenital defect.

McFarlane (1965) is the primary source describing the pathology of dystocic lambs and that work has since been built upon by other authors. (Haughey 1973a, 1973b) described the differences in vascular lesions of the central nervous system (CNS) of lambs dying during parturition (predominantly brain haemorrhage) as opposed to post-parturition (predominantly spinal cord haemorrhage). This work was the precursor to the development of the sub-categories of dystocia described by Holst (2004) and applied by Holst *et al*. (2002) and Refshauge *et al*. (2016). Dutra and Banchero (2011) further contributed to this topic through their work on the role of hypoxia in birth injury deaths, particularly in multiple births and those with long duration of the birth. Together the abovementioned work has led to a broad acceptance that birth injury is a form of dystocia and a predisposing factor that leads to death in the few days following birth (Refshauge *et al.* 2016; Horton *et al.* 2018). In the Sheep CRC INF starvation was the single largest cause of death (25%), but the 3 categories of dystocia together (primary dystocia, stillbirth and birth injury) accounted for 48% of deaths (Refshauge *et al*. 2016). Horton *et al.* (2018) further described dystocia in terms of low and high birth weight types, which have different causes and contributing factors of death.

In cases of primary dystocia, otherwise described by Holst (2004) as Dystocia A or 1, the lamb was viable prior to birth. They become wedged in the birth canal dcentral uring parturition due either to foeto-pelvic disproportion, malpresentation or uterine inertia. These lambs show evidence of subcutaneous oedema around the head and neck, and possibly the front lower limbs, and severe vascular lesions, particularly of the brain, but also often of the spinal cord (Haughey 1973b). These lambs have not walked or breathed, and birth often requires assistance. Without assistance, this form of dystocia is not only fatal to the lamb, but in Australia's extensive production systems, also to the ewe (Jacobson *et al*. 2020).

Stillborn (Refshauge *et al*. 2016) or Dystocia B or 2 (Holst 2004) are described as lambs that die during birth or briefly survive a difficult birth process, show signs of central nervous system (CNS) haemorrhage or hypoxia during birth, may have walked and breathed, and do not show any kidney fat metabolism.

Lambs that die from birth injury or Dystocia C or 3 (Holst 2004) are those that show significant brain and/or spinal cord haemorrhage and also have exhausted kidney fat reserves. Without autopsy these deaths that can be easily mistaken for starvation or exposure (Haughey 1973b). These lambs often survive a few days but eventually die due to starvation, mismothering or exposure.

Birth-injured lambs are impaired in their ability to maintain body temperature and have impeded behavioural abilities critical to their survival such as responsiveness to the dam, standing, teat-seeking and suckling (Dwyer and Morgan 2006). Dutra *et al.* (2007) regarded that these impairments are largely associated with sub-lethal hypoxia arising from lengthy a birth process. Similarly, Nowak et al. (2007) and Everett-Hincks and Duncan (2008) recognised that lambs which suffer a birth injury are likely to die from cold exposure or starvation, but the primary cause of death remains the birth injury.

Horton *et al*. (2018) attempted to model dystocia risk in the Sheep CRC INF. Dystocia risk was difficult to predict, and there were two types – high and low birth weight dystocia, and that the risk factors varied for low and high birth weight lambs. Dystocia B (stillbirth) and C (birth injury) were most commonly associated with dam age and litter size, with older ewes and multiples (low birth weight) at greater risk. Dystocia A was not associated with dam age and predominantly affected high birth weight singles.

Overall, the value of lamb autopsies in better understanding the causes of perinatal lamb loss cannot be overstated. Without autopsies, the cause of death for many lambs dying of birth injuries would be misdiagnosed as starvation or exposure. It is also self-evident that the effort required to undertake a large number of lamb autopsies is prohibitive in large flocks or under extensive conditions. Loss of lamb carcases due to secondary predation can pose additional problems. An automated method to identify dystocic lambing events would provide a valuable alternative.

Starvation, Exposure and Predation

Starvation has been described as part of a complex comprising starvation, mismothering, and exposure, sometimes referred to as the SME complex (Hinch and Brien 2014). The probable cause of these deaths are associated with any or all of the following; physiological handicap arising from placental insufficiency; deviant ewe or lamb behaviour; mismothering due to poor management or other reasons; misadventure; inadequate milk supply or teat/udder issues; and cold-induced starvation (Haughey 1991).

Exposure deaths are regarded as those that would likely have survived in the absence of an adverse weather event. These lambs have breathed, possibly walked, not metabolised fat, and show no evidence of the subcutaneous oedema typical of primary dystocia or significant CNS lesions normally associated with Dystocia B or C (Refshauge *et al*. 2016). Haughey (1973a) reported that primary exposure is indicated by yellowish-coloured subcutaneous oedema of the lower limbs and tail. However, Refshauge *et al.* (2016) noted that this peripheral oedema is not always observed. Similarly, Alexander *et al.* (1980b) had suggested peripheral oedema was an unreliable indicator of primary exposure. Therefore, knowledge of the chill index on the day of death could be a useful additional aid in the determination of exposure as cause of death (Broster *et al.* 2012).

In Australia the main predators of neonatal lambs are foxes, wild dogs, pigs, wedge-tailed eagles and crows (Rowley 1970). Control of the ground-dwelling predators is regarded as good industry practice to aid lamb survival (MLA 2008). However, Greentree *et al.* (2000) examined predation on five properties in south-eastern Australia, found that fox predation was only responsible for approximately 1-5% of overall lamb mortality. Saunders *et al.* (2010) quote fox predation rates ranging from 1-30%. These findings suggest that the impacts not only of foxes, but also of other main predators in Australia are likely highly dependent upon the geographic region, the type of predators present and their behaviours, and environmental circumstances.

According to Dennis (1974) and Holst (2004) producers tend to overestimate mortality due to predation and that lambs believed to have been predated are in fact already compromised for some other reason (birth injury, mismothered etc.) prior to predation. Results collected by the SheepCRC IFN confirm the variability of the rate of predation, with predation accounting for 0 – 18% depending on site and year (Geenty *et al.* 2014; Refshauge *et al.* 2016).

Collectively, it can be argued that at least a proportion of lambs lost due to starvation, exposure and predation can be explained by a lack of maternal bond and care. The term ‘mismothering’ is often employed to describe this phenomenon. Interestingly, a lamb vigour analysis investigating lamb vocalisation found evidence that ewes can discriminate between the bleat of a healthy lamb and the bleat of a lamb with neurobehavioral deficiencies (Morton *et al.* 2017; Morton *et al.* 2018). This raises the possibility that at least a proportion of ewes abandoning their lamb do so in response to birth injury damage in the lamb. This damage may be subtle and hence not detectable through autopsy, and given time, the lamb will recover to full function. However, in a field setting, the ewe will feel compelled to seek the safety of the flock before this can happen. Especially for twin bearing ewes, this makes evolutionary sense, as the safety of one lamb may outweigh the risk of losing both twin-born lambs.

Other causes of mortality

Minor causes of neonatal mortality include infection, congenital defect, death *in utero*, and misadventure (Refshauge *et al.* 2016). Dennis (1993) reported that 0.2 to 2.0% of lambs are born with a congenital deformity, of either genetic or environmental origin in Australia and New Zealand, while Woolliams *et al.* (1983) reported for various UK breeds and crosses a rate of 2% mortality arising from congenital deformities.

In individual flocks and years, deaths due to infectious diseases or trace element deficiencies such as selenium or iodine can be considerable. Management practices such as vaccination of ewes prior to lambing for clostridial diseases and supplementation or fertilizer application of trace elements to pastures are recommended to reduce the prevalence of these sources of loss (Blackwood and Duddy 2009). Subclinical deficiency levels may not be adequately addressed by such management practices, and increased awareness of the elevated requirements for trace elements in highly productive flocks may be beneficial (Schmoelzl and Cowley 2016). Selenium deficiency can result in white muscle disease and is diagnosed at autopsy by white grit in the heart muscle (Holst 2004). Iodine deficient lambs have low metabolic rate, are prone to hypothermia, have impaired neonatal behaviours and can be diagnosed from the ratio of thyroid glands weight to birth body weight (Everett-Hincks and Duncan 2008; Robertson *et al.* 2008). Iodine deficiency is difficult to ameliorate in the immediate term in lambs and Everett-Hincks and Duncan (2008) recommend ewes should be supplemented the following season with iodine, especially if grazing brassicas which can be goitrogenic.

Influencing lamb survival through management and genetics

Management for improved lamb survival

Neonatal survival is dependent upon a wide range of often interacting and confounding factors which have been reviewed in depth by Hinch and Brien (2014) and Jacobson *et al.* (2020). Components of the environment, including the weather and flock management practices, interact with and confound inherent factors associated with both the ewe and the lamb(s) in the period prior to, during, and following birth. The high degree of interconnectedness of factors contributing to neonatal mortality is perhaps the reason it is so difficult to make gains in neonatal survival through improvements in single factors.

The importance of environmental factors experienced immediately around parturition has been readily observable and early research focussed interventions to mitigate adverse conditions, specifically temperature and wind chill, through shelter provision (Alexander and Lynch 1976; Lynch and Alexander 1977; Alexander *et al.* 1979). This work also lead to the issue of Warnings to Sheep Graziers through the Australian Government Bureau of Meteorology (Alexander *et al.* 1980a; Holst and Cullis 1982). Weather conditions are particularly relevant to lambs born to ewes in poor body condition which have been shown to cool quicker and to be less capable of regaining body temperature in the hours following birth than those from well-fed ewes (Alexander 1962).

Symonds *et al.* (1992) demonstrated that cold exposure of late pregnant ewes by shearing in winter confers a degree of survival improvement in neonatal lambs through higher birth weight, higher thermogenic activity of brown adipose tissue, and reduced glycogen mobilisation when exposed to cold conditions. A similar response to mid-pregnancy shearing of Romney ewes in commercial conditions was reported by (Kenyon *et al.* 2006), with birth weights approximately 0.4kg higher in twin and triplet lambs born to shorn ewes compared to woolly ewes. Kenyon *et al*. (2006) suggest this maybe a useful management practice for flocks with high proportions of multiple births where low birth weights would ordinarily put those lambs at risk from starvation and exposure. Shearing of ewes may have a direct influence on the behaviour of newborn lambs, especially in cold environmental conditions, as shown by Labeur *et al.* (2020) who found that lambs born to ewes shorn in mid-pregnancy performed better in lamb vigour tests after a cold challenge than did those born to unshorn ewes.

Ewe nutrition prior and during pregnancy is perhaps the most influential factor of the ewe affecting lamb survival and have been extensively covered elsewhere and hence shall not be comprehensively discussed here. It has been known for a long time that ewe nutrition during pregnancy impacts lamb survival, largely through effects on birth weight and, as a consequence, body temperature of the neonate lamb (Alexander and McCance 1958; Mellor 1983). Aside from effects on lamb birth weight, malnourished ewes show poor maternal behaviour, low attachment to the lamb, and are likely to abandon their lambs, especially when giving birth to twins (Dwyer 2003). Management strategies for optimised body condition of the ewe have been demonstrated to be beneficial for reproductive success (Everett-Hincks *et al.* 2005; Kenyon *et al.* 2009; Kenyon *et al.* 2012). Ewe nutrition in the last third of pregnancy determines the ultimate birth weight, with lamb survival positively correlated with ewe condition score in late pregnancy (Kleeman and Walker 2005). Lamb birthweight is highly correlated to survival to weaning with apparently little difference for optimum weights between single or multiple birth types (Paganoni *et al.* 2014; Geenty *et al.* 2014). Improved twin-bearing ewe management programs resulted in increased twin lamb survival (Hocking Edwards *et al.* 2011).

Managing ewe nutrition in relation to body condition score is a key component of the Lifetime wool industry education program (LifetimeWool 2016). Improved lamb survival to weaning can be achieved by optimising ewe body condition prior to birth; differential management of single and twin bearing ewes during late pregnancy; and lower stocking density, especially of twin-bearing ewes during lambing (Behrendt *et al.* 2011; Hocking Edwards *et al.* 2011; Oldham *et al.* 2011; Thompson *et al.* 2011). More recently, a separate study conducted in southern NSW reported that best practice management of ewes according to LifetimeWool guidelines resulted in lamb survival rates of 89% and 71% for singles and twins, respectively (Allworth *et al.* 2017).

Additional contributing factors which can be addressed through nutritional or improved pasture management are mineral-deficiencies and metabolic diseases, including deficiencies in calcium and magnesium (Friend *et al.* 2020), addressing oxidative stress (Masters 2018) and the already mentioned supplementation or treatment with selenium and iodine (Knowles and Grace 2007; Kerslake *et al.* 2010; van Ryssen *et al.* 2013; Knowles and Grace 2015; Williams *et al.* 2017). The effects of deficiencies and metabolic disease are often particularly impactful in difficult seasons, be it through limited feed-base in drought years or when inclement weather coincides with lambing. This complicates research into efficacy of nutritional treatments. Replacing the focus on mortalities as endpoint with a measurement of prolonged lambing would reduce the uncontrollable study element and offer new opportunities to study targeted interventions.

Influence of genetic factors on lamb survival

Difference in reproductive behaviour between breeds have long been a topic of discussion. Purebred Merino sheep which comprise the majority of breeding ewes in Australia have long been regarded to have less reproductive success compared to Merino crosses and other maternal and terminal breeds (Fogarty 1972); (Holst 2002). Paganoni *et al.* (2014) reported overall survival rates of 82, 85, and 78% for lambs born to Merino ewes mated to Merino, Border Leicester/Merino crosses, or terminal sires, respectively, and survival of 88% of lambs born to Border Leicester Merino ewes mated to terminal sires. The average lamb loss rate from scanning to marking was reported as 21% for Merinos and 13% for Merino crosses and other breeds in a survey of sheep breeders in southern NSW by Allworth *et al*. (2017).

Paganoni *et al.* (2014) found birthweight the largest determinant of survival of lambs with maximum survival observed for lambs weighing between 5 and 7 kg across birth types and across ewe and sire breeds. It is worth noting that in that study, Merino ewes were on average 11 kg lighter at conception than maternal breed cross ewes. To reach a lamb birthweight of 5 kg, Merino ewes would have to produce 8.8 or 17.7% of their own body mass in litter weight for single/twin pregnancies, respectively, whereas the proportion for maternal cross ewes would have been 7.4 or 14.8%, based on figures reported by Paganoni *et al.* (2014), highlighting the higher level of maternal efficiency required of Merino ewes in comparison to cross bred ewes.

Dutra and Banchero (2011) reported ewe breed differences in body size and pelvic proportions which influence lamb survival through effects on duration of parturition and risk of physical and/or hypoxic damage during birth. Within the Merino breed, Hergenhan *et al.* (2014) observed between-sire variation in lamb vigour and subsequent survival which may be exploited in genetic selection programs for Australian production systems.

Reproduction as a genetic trait is currently reported to the Australian sheep industry through the trait Numbers of Lambs Weaned (NLW) and accounts for between 2 and 26% of selection emphasis within MERINOSELECT indices (Walkom and Brown 2014). Numbers of Lambs Weaned is a composite trait that incorporates components of fertility, litter size and lamb survival to weaning. Heritability for NLW has been estimated to range from h2=0.05-0.07 (Safari *et al.* 2007). Genetic analyses of lamb autopsy traits found low heritability for these traits but positive correlations with lamb survival and with lambing ease, indicating that use of lambing ease as a selection trait may support improved lamb survival (Brown *et al.* 2014). Maternal effects appeared stronger than direct lamb effects in this analysis. Bunter *et al.* (2018) found maternal rearing-ability of ewes can be genetically considered as separate traits depending on litter size and argue that simultaneous selection for improvements in both number of lambs born and lamb survival is possible.

Breed differences show that there are genetic mechanisms at play that affect lamb survival. It has been a challenge to identify traits that allow genetic improvement of lamb survival, and progress has been slow. The complex nature of lamb survival as a genetic trait together with high variability in environmental conditions means that breaking the trait down into component traits may be a promising alternative.

Improvement of lamb survival could be seen as an analogy to risk mitigation in health and safety of workplaces. In this field, the focus has increasingly moved away from avoidance of injury or death which typically occurs in 'black swan' events, that is after cumulation of several pre-disposing risk factors. Instead, the focus has turned on building a culture where each of these risks is managed proactively (Cooper 2018). Applied to lamb survival, this concept will require re-consideration of underlying risk factors, and development of phenotypes that allow improvement of those component traits.

Dystocia as a phenotype

Dystocia has been demonstrated to be, directly or indirectly, the single largest contributor to lamb losses. Heritability of dystocia has been estimated to be low (Brown *et al.* 2014) but it is important to keep in mind that this is based on dystocia leading to lamb death. The total number of dystocia, or prolonged lambing events, is however much higher overall, and the ability to measure those events would allow description of a new phenotype, that of prolonged parturition, regardless of outcome for the lamb. This might provide more opportunity of genetic variation to be expressed. Hence, measuring dystocia in all birth events, not only in those leading to neonatal death via autopsies, could provide a more highly heritable component trait compared to the composite trait NLW.

Dystocia, or prolonged labour, is challenging to measure. The term describes a longer than normal active stage of parturition, characterised by dilation of the cervix and regular abdominal contractions (Selin *et al.* 2008). In a research setting observing lambing ewes, a compromise must be found between the ability to closely observe the lambing ewe and a requirement for the ewe to express natural lambing behaviours. We have undertaken repeated studies of ewes lambing in an enclosure of about 0.1 ha area in groups of twenty at a time under day and night video surveillance (Schmoelzl *et al.* 2016). From a subset of the collected data, we observed ewes showed more maternal care behaviour immediately after a normal birth compared to after a prolonged birth (unpublished observation). This observation supports the notion that prolonged labour can be an important factor in disrupting the development of the ewe-lamb bond as postulated by Nowak *et al.* (2011).

To investigate dystocia as a trait, we need to be able to detect dystocia on larger numbers of lambing ewes. The first step towards this goal, is the detection of the lambing event itself. Previous studies in lambing ewes using global navigation satellite system (GNSS) technology found differences in mean distances between ewes and her peers, and in the mean daily speed observed from GNSS data, although these metrics failed to identify the time of lambing (Dobos *et al.* 2014). In our studies, we have developed a sensor-based device to detect the lambing event from the movement pattern of the ewe (Smith *et al.* 2020). Current efforts are focussed on differentiating between prolonged or normal labour. Augmentation of lambing detection with behavioural classification algorithms may help achieve this goal (Fogarty *et al.* 2020; Hu *et al.* 2020). With the establishment of such a research tool, we will be able to undertake new research to investigate research questions previously impossible to answer directly, such as understanding the energetic demands of the ewe to deliver lambs in a timely manner. Collaborative opportunities within the Australian research community have been identified to ensure this work can have the most effective reach and impact possible.

Conclusions

Improved lamb survival is a well-established focal point for livestock research in Australia. Optimised management programs for improved body conditions have been established and the benefits of improved management demonstrated but challenges remain to improve lamb survival. Differences in reported responses to improved management may point to interactions between environment, management and genetics in different regions. Micronutrient management has received less attention in recent years although its importance may increase further as sheep flocks are pushed towards increased productivity. Other management interventions, such as mid-pregnancy shearing, may affect lambing outcomes in multiple ways, including increased lamb birthweight and potentially improved ability of the lamb to cope with cold environmental conditions at birth. Prolonged lambing, or dystocia, has been conclusively shown to be a main contributor to lamb losses and can be caused by obstruction due to foetal size relative to ewe size or malpresentation, especially of twins, but also through lack of uterine tone in the ewe. Breed differences in lamb survival rates point to the role of genetic factors although genetic selection for improved lamb survival has been difficult to achieve to date. Genetically, lamb survival appears to be more strongly explained as a maternal trait than as a lamb trait, highlighting that increased focus on maternal rearing ability is warranted. A sensor-based approach to detect dystocia will allow increased research efforts to be undertaken to understand what leads to lack of lambing progress and how to improve the ability of ewes to cope with the energetic demands of lambing in extensive systems.

Acknowledgements

The authors thank the anonymous reviewers for their help and constructive feedback. We hope we have done them justice.

References

Alexander, G (1961) Energy expenditure and mortality in new-born lambs, Proceedings of the 4th International Congress on Animal Reproduction, The Hague, 630 – 37.

Alexander, G (1962) Temperature regulation in the new-born lamb 4. The effect of wind and evaporation o f water from the coat on metabolic rate and body temperature. Australian Journal of Agricultural Research 13, 82 - 99.

Alexander, G, Bradley, LR, Stevens, D (1993) Effect of age and parity on maternal behaviour in single-bearing Merino ewes. Australian Journal of Experimental Agriculture 33, 721 - 728.

Alexander, G, Lynch, JJ (1976) Phalaris windbreaks for shorn and fleeced lambing ewes. Proceedings of the Australian Society of Animal Production 11, 161 - 164.

Alexander, G, Lynch, JJ, Mottershead, BW (1979) Use of shelter and slection of lambing sites by shorn and unshorn ewes in paddocks with closely or widely spaced shelters. Applied Animal Ethology 5, 51 - 69.

Alexander, G, Lynch, JJ, Mottershead, BW, Donnelly, JB (1980a) Reduction in lamb mortality by means of grass wind-breaks: results of a five-year study. Proceedings of the Australian Society of Animal Production 13, 329-332.

Alexander, G, Lynch, JJ, Mottershead, BW, Donnelly, JB (1980b) Reduction in lamb mortality due to grass wind-breaks: results of a five-year study. Proceedings of the Australian Society of Animal Production 13, 329 - 332.

Alexander, G, McCance, I (1958) Temperature regulation in the new-born lamb. 1. Changes in rectal temperature within the first six hours of life. Australian Journal of Agricultural Research 9, 339-347.

Alexander, G, Stevens, D, Kilgour, R, de Langen, H, Mottershead, BE, Lynch, JJ (1983) Separation of ewes from twin lambs: Incidence in several sheep breeds. Applied Animal Ethology 10, 301-317.

Alexander, G, Williams, D (1968) Shivering and non-shivering thermogenesis during summit metabolism in young lambs. Journal of Physiology 198, 251 - 276.

Allworth, MB, Wrigley, HA, Cowling, A (2017) Fetal and lamb losses from pregnancy scanning to lamb marking in commercial sheep flocks in southern New South Wales. Animal Production Science 57, 2060-2065.

AMSEA (2021) MLP Project. Available at https://merinosuperiorsires.com.au/mlp-project/; verified 3rd May 2021.

Behrendt, R, Burgel, A, Bailey, A, Barber, P, Curnow, M, Gordon, D, Hocking Edwards, J, Oldham, C, Thompson, A (2011) On-farm paddock-scale comparisons across southern Australia confirm that increasing the nutrition of Merino ewes improves their production and the lifetime performance of their progeny. Animal Production Science 51, 805.

Bell, A (2018) Standing on giant shoulders: A personal recollection of the lives and achievements of eminent animal scientists 1965-2015. Animal Production Science 59, 1-34.

Bickell, SL, Nowak, R, Poindron, P, Ferguson, D, Blache, D (2010) Maternal behaviour at parturition in outdoor conditions differs only moderately between single-bearing ewes selected for their calm or nervous temperament. Animal Production Science 50, 675-682.

Bickell, SL, Nowak, R, Poindron, P, Sebe, F, Chadwick, A, Ferguson, D, Blache, D (2009) Temperament does not affect the overall establishment of mutual preference between the mother and her young in sheep measured in a choice test. Developmental Psychobiology 51, 429 - 437.

Blackwood, I, Duddy, G (2009) Assessing stock feed additives and mineral supplements. Primefact 656. Industry and Investment NSW. Retrieved from: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0019/304912/Assessing-stock-feed-additives-and-mineral-supplements.pdf; verified 3rd May 2021.

Brien, FD, Hinch, GN, Van der Werf, JHJ, Brown, DJ, Swan, AA (2011) Selection strategies for the genetic improvement of reproductive performance in sheep. Proceedings of the Association for Advancement of Animal Breeding and Genetics 19, 151-158.

Broster, JC, Rathbone, DP, Robertson, SM, King, BJ, Friend, MA (2012) Ewe movement and ewe-lamb contact levels in shelter are greater at higher stocking rates. Animal Production Science 52, 502-506.

Brown, DJ, Jones, RM, Hinch, GN (2014) Genetic parameters for lamb autopsy traits. Animal Production Science 54, 736-744.

Bunter, KL, Swan, AA, Brown, DJ, Brien, FD, Smith, J (2018) Litter size at lambing influences genetic evaluation of maternal rearing ability. Animal Production Science 58, 791-800.

Cooper M.D. (2018) The Safety Culture Construct: Theory and Practice. In: Gilbert C., Journé B., Laroche H., Bieder C. (eds) Safety Cultures, Safety Models. SpringerBriefs in Applied Sciences and Technology. Springer, Cham. https://doi.org/10.1007/978-3-319-95129-4_5

Dennis, SM (1974) Perinatal Lamb Mortality in Western Australia: 1. General Procedures and Results. Australian Veterinary Journal 50, 443-449.

Dennis, SM (1993) Congenital Defects of Sheep. Veterinary Clinics of North America: Food Animal Practice 9, 203-217.

Dobos, RC, Dickson, S, Bailey, DW, Trotter, MG (2014) The use of GNSS technology to identify lambing behaviour in pregnant grazing Merino ewes. Animal Production Science 54, 1722-1727.

Dutra, F, Banchero, G (2011) Polwarth and Texel ewe parturition duration and its association with lamb birth asphyxia. Journal of Animal Science 89, 3069-3078.

Dutra, F, Quintans, G, Banchero, G (2007) Lesions in the central nervous system associated with perinatal lamb mortality. Australian Veterinary Journal 85, 405-413.

Dwyer, CM (2003) Behavioural development in the neonatal lamb: effect of maternal and birth-related factors. Theriogenology 59, 1027 - 1050.

Dwyer, CM, Morgan, CA (2006) Maintenance of body temperature in the neonatal lamb: effects of breed, birth weight, and litter size. Journal of Animal Science 84, 1093-1101.

Everett-Hincks, JM, Blair, HT, Stafford, KJ, Lopez-Villalobos, N, Kenyon, PR, Morris, ST (2005) The effect of pasture allowance fed to twin- and triplet-bearing ewes in late pregnancy on ewe and lamb behaviour and performance to weaning. Livestock Production Science 97, 253-266.

Everett-Hincks, JM, Cullen, NG (2009) Genetic parameters for ewe rearing performance. Journal of Animal Science 87, 2753-8.

Everett-Hincks, JM, Duncan, SJ (2008) Lamb post-mortem protocol for use on farm: To diagnose primary cause of lamb death from birth to 3 days of age. The Open Veterinary Science Journal 2, 55 - 62.

Fogarty, ES, Swain, DL, Cronin, GM, Moraes, LE, Trotter, M (2020) Can accelerometer ear tags identify behavioural changes in sheep associated with parturition? Animal Reproduction Science 106345.

Fogarty, NM (1972) Crossbreeding for lamb production 1. Survival and growth of first cross lambs. Australian Journal of Experimental Agriculture and Animal Husbandry 12, 234 - 239.

Fowler, DG (2007) AHW.131 Lamb marking performance for ultrasound scanned ewes in Australian sheep flocks. Meat and Livestock Australia, Sydney. ISBN 9781741911589.

Friend, MA, Bhanugopan, MS, McGrath, SR, Edwards, JH, Hancock, S, Loudon, K, Miller, D, McGilchrist, P, Refshauge, G, Robertson, SM, Thompson, AN, Masters, DG (2020) Do calcium and magnesium deficiencies in reproducing ewes contribute to high lamb mortality? Animal Production Science 60, 733-751.

Geenty, KG, Brien, FD, Hinch, GN, Dobos, RC, Refshauge, G, McCaskill, M, Ball, AJ, Behrendt, R, Gore, KP, Savage, DB, Harden, S, Hocking-Edwards, JE, Hart, K, van der Werf, JHJ (2014) Reproductive performance in the Sheep CRC Information Nucleus using artificial insemination across different sheep-production environments in southern Australia. Animal Production Science 54, 715-726.

Greentree, C, Saunders, G, Mcleod, L, Hone, J (2000) Lamb predation and fox control in south-eastern Australia. Journal of Applied Ecology 37, 935-943.

Haughey, KG (1973a) Vascular abnormalities in the central nervous system associated with perinatal lamb mortality. 1. Pathology. Australian Veterinary Journal 49, 1-8.

Haughey, KG (1973b) Vascular abnormalities in the central nervous system associated with perinatal lamb mortality. 2. Association of the abnormalities with recognised lesions. Australian Veterinary Journal 49, 9-15.

Haughey, KG (1983) Selective breeding for rearing ability as an aid to improving lamb survival. Australian Veterinary Journal 60, 361-363.

Haughey, KG (1991) Perinatal lamb mortality: its investigation, causes and control. Journal of the South African Veterinary Association 62, 78–91. Journal of the South African Veterinary Association 62, 78-91.

Hergenhan, RL, Hinch, GN, Ferguson, DM (2014) Sire effects on neonatal lamb vigour and following-behaviour. Animal Production Science 54, 745-752.

Hinch, GN, Brien, F (2014) Lamb survival in Australian flocks: a review. Animal Production Science 54, 656-666.

Hocking Edwards, JE, Copping, KJ, Thompson, AN (2011) Managing the nutrition of twin-bearing ewes during pregnancy using Lifetimewool recommendations increases production of twin lambs. Animal Production Science 51, 813-820.

Holst, P, Fogarty, N, Stanley, D (2002) Birth weights, meningeal lesions, and survival of diverse genotypes of lambs from Merino and crossbred ewes. Crop and Pasture Science 53, 175-181.

Holst, PJ (2004) Lamb autopsy, notes on a procedure for determining cause of death. NSW Agriculture and Sheep CRC, Retrieved from: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/177783/lamb-autopsy.pdf; verified 3rd May 2021.

Holst, PJ, Cullis, BR (1982) Meteorological data as a management aid for reduction of lamb losses from inclement weather. Proceedings of Australian Society of Animal Production 14, 432-434.

Holst, PJ, Fogarty, N.M. and Stanley, D.M. (2002) Birth weights, meningeal lesions, and survival of diverse genotypes of lambs from Merino and crossbred ewes. Australian Journal of Agricultural Research 53, 175 - 181.

Horton, BJ, Corkrey, R, Hinch, GN (2018) Estimation of risk factors associated with difficult birth in ewes. Animal Production Science 58, 1125-1132.

Hu, S, Ingham, A, Schmoelzl, S, McNally, J, Little, B, Smith, D, Bishop-Hurley, G, Wang, Y-G, Li, Y (2020) Inclusion of features derived from a mixture of time window sizes improved classification accuracy of machine learning algorithms for sheep grazing behaviours. Computers and Electronics in Agriculture 179, 105857.

Hughes, KL, Hartely, WJ, Haughey, KG, McFarlane, D (1964) A study of perinatal mortality of lambs from the Oberon, Orange and Monaro districts of N.S.W. Proceedings of the Australian Society of Animal Production 5, 92-99.

Jacobson, C, Bruce, M, Kenyon, PR, Lockwood, A, Miller, D, Refshauge, G, Masters, DG (2020) A review of dystocia in sheep. Small Ruminant Research 192, 106209.

Kelly, O, Hebart, M, Brien, F, Pitchford, W (2016) Lamb survival should be considered separate genetic traits across different birth types. Animal Production in Australia: Proceedings of the 31st Biennial Conference of the Austrlian Society of Animal Production 31, 1205.

Kenyon, PR, Blair, HT, Jenkinson, CMC, Morris, ST, Mackenzie, DDS, Peterson, SW, Firth, EC, Johnston, PL (2009) The effect of ewe size and nutritional regimen beginning in early pregnancy on ewe and lamb performance to weaning. New Zealand Journal of Agricultural Research 52, 203-212.

Kenyon, PR, Hickson, RE, Hutton, PG, Morris, ST, Stafford, KJ, West, DM (2012) Effect of twin-bearing ewe body condition score and late pregnancy nutrition on lamb performance. Animal Production Science 52, 483-490.

Kenyon, PR, Revell, DK, Morris, ST (2006) Mid-pregnancy shearing can increase birthweight and survival to weaning of multiple-born lambs under commercial conditions. Australian Journal of Experimental Agriculture 46, 821-825.

Kerslake, JI, Kenyon, PR, Stafford, KJ, Morris, ST, Morel, PCH (2010) Can maternal iodine supplementation improve twin-and triplet-born lamb plasma thyroid hormone concentrations and thermoregulation capabilities in the first 24-36 h of life? Journal of Agricultural Science 148, 453-463.

Kleeman, DO, Walker, SK (2005) Fertility in South Australian commercial Merino flocks: sources of reproductive wastage. Theriogenology 63, 2075 - 2088.

Knowles, SO, Grace, ND (2007) A practical approach to managing the risks of iodine deficiency in flocks using thyroid-weight:birthweight ratios of lambs. New Zealand Veterinary Journal 55, 314-318.

Knowles, SO, Grace, ND (2015) Serum total iodine concentrations in pasture-fed pregnant ewes and newborn lambs challenged by iodine supplementation and goitrogenic kale. Journal of Animal Science 93, 425-432.

Kubeil, L (2017) E.REP.1404 Informing future sheep extension strategies to improve reproduction and related welfare outcomes. Meat and Livestock Australia.

Labeur, L, Small, AH, Hinch, GN, McFarlane, JR, Schmoelzl, S (2020) Mid- and late-pregnancy ewe shearing affects lamb neonatal reactivity and vigour. Applied Animal Behaviour Science 231, 105065.

Lambe, NR, Conington, J, Bishop, SC, Waterhouse, A, Simm, G (2001) A genetic analysis of maternal behaviour score in Scottish Blackface sheep. Animal Science 72, 415-425.

Lane, J (2015) B.AHE.0010 Priority list of endemic diseases for the red meat industries. Meat and Livestock Australia. ISBN 9781741918946.

LifetimeWool (2016) Lifetime ewe management – more lambs, better wool, healthy ewes. Retrieved from: http://www.lifetimewool.com.au/LTEM.aspx; verified 3rd May 2021.

Luff, AF (1980) A service for all seasons. Final Report Australian Wool Corporation Project K/1/1051. Melbourne.

Lynch, JJ, Alexander, G (1977) Sheltering behaviour of lambing Merino sheep in relation to grass hedges and artificial windbreaks. Australian Journal of Agricultural Research 28, 691 – 701.

Masters, DG (2018) Practical implications of mineral and vitamin imbalance in grazing sheep. Animal Production Science 58, 1438-1450.

McFarlane, D (1965) Perinatal lamb losses. I. An autopsy method for the investigation of perinatal losses. New Zealand Veterinary Journal 13, 116-135.

Mellor, DJ (1983) Nutritional and placental determinants of foetal growth rate in sheep and consequences for the newborn lamb. British Veterinary Journal 139, 307 - 324.

MLA (2008) Making more from sheep, Wean more lambs, Module 10. Australian Wool Innovation Ltd and Meat and Livestock Australia, Retrieved from: http://www.makingmorefromsheep.com.au/wean-more-lambs; verified 3rd May 2021.

Morton, CL, Hinch, G, Small, A (2017) Distress vocalization delay in the neonate lamb as a neurobehavioral assessment tool. Developmental Psychobiology 59, 523-534.

Morton, CL, Hinch, G, Small, A, McDonald, PG (2018) Flawed mothering or infant signaling? The effects of deficient acoustic cues on ovine maternal response. Developmental Psychobiology 60, 975-988.

Nowak, R, Keller, M, Lévy, F (2011) Mother–Young Relationships in Sheep: A Model for a Multidisciplinary Approach of the Study of Attachment in Mammals. Journal of Neuroendocrinology 23, 1042-1053.

Nowak, R, Keller, M, Val-Laillet, D, Lévy, F (2007) Perinatal visceral events and brain mechanisms involved in the development of mother–young bonding in sheep. Hormones and Behavior 52, 92-98.

Oldham, CM, Thompson, AN, Ferguson, MB, Gordon, DJ, Kearney, GA, Paganoni, BL (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.

Paganoni, BL, Ferguson, MB, Kearney, GA, Thompson, AN (2014) Increasing weight gain during pregnancy results in similar increases in lamb birthweights and weaning weights in Merino and non-Merino ewes regardless of sire type. Animal Production Science 54, 727-735.

Plush, KJ, Hebart, ML, Brien, FD, Hynd, PI (2011) The genetics of temperament in Merino sheep and relationships with lamb survival. Applied Animal Behaviour Science 134, 130-135.

Refshauge, G, Brien, FD, Hinch, GN, van de Ven, R (2016) Neonatal lamb mortality: factors associated with the death of Australian lambs. Animal Production Science 56, 726-735.

Robertson, SM, Friend, MA, King, BJ (2008) Mild congenital goitre increases lamb mortality in southern New South Wales. Australian Journal of Experimental Agriculture 48, 995-998.

Rowley, I (1970) Lamb predation in Australia: incidence, predisposing conditions, and the identification of wounds. CSIRO Wildlife Research 15, 79-123.

Safari, E, Fogarty, NM, Gilmour, AR, Atkins, KD, Mortimer, SI, Swan, AA, Brien, FD, Greeff, JC, van der Werf, JHJ (2007) Across population genetic parameters for wool, growth, and reproduction traits in Australian Merino sheep. 2. Estimates of heritability and variance components. Australian Journal of Agricultural Research 58, 177-184.

Saunders, GR, Gentle, MN, Dickman, CR (2010) The impacts and management of foxes Vulpes vulpes in Australia. Mammal Review 40, 181-211.

Schmoelzl, S, Cowley, F (2016) The case for pre-parturient selenium and iodine supplementation of ewes for improving lamb survival. Animal Production Science 56, 1263-1274.

Schmoelzl, S, Little, B, McNally, J, Small, A, Ingham, A (2016) Development of a remote sensing device to detect duration of parturition in ewes. Animal Production 2016: Proceedings of the 31st Conference of the Australian Society for Animal Production. 31, 1245.

Selin, L, Wallin, G, Berg, M (2008) Dystocia in labour – risk factors, management and outcome: a retrospective observational study in a Swedish setting. Acta Obstetricia et Gynecologica Scandinavica 87, 216-221.

Smith, D, McNally, J, Little, B, Ingham, A, Schmoelzl, S (2020) Automatic detection of parturition in pregnant ewes using a three-axis accelerometer. Computers and Electronics in Agriculture 173, 105392.

Smith, ID (1964) Ovine neonatal mortality in western Queensland. Proceedings 5th Conference of the Australian Society of Animal Production. Aust. Soc. Anim. Prod. 5, 100-106.

Symonds, ME, Bryant, MJ, Clarke, L, Darby, CJ, Lomax, MA (1992) Effect of maternal cold exposure on brown adipose tissue and thermogenesis in the neonatal lamb. The Journal of Physiology 455, 487-502.

Thompson, AN, Ferguson, MB, Campbell, AJD, Gordon, DJ, Kearney, GA, Oldham, CM, Paganoni, BL (2011) Improving the nutrition of Merino ewes during pregnancy and lactation increases weaning weight and survival of progeny but does not affect their mature size. Animal Production Science 51, 784-793.

van Ryssen, JBJ, Coertze, RJ, Smith, MF (2013) Time-dependent effect of selenium supplementation on the relationship between selenium concentrations in whole blood and plasma of sheep. Small Ruminant Research 112, 85-90.

Walkom, SF, Brown, DJ (2014) Breeding for resilience and resistance in Merino Sheep. In 'Breeding Focus 2014 - Improving Resilience.' pp. 141-156.

Williams, JR, Williams, NE, Kendall, NR (2017) The efficacy of supplying supplemental cobalt, selenium and vitamin B12 via the oral drench route in sheep. Livestock Science 200, 80-84.

Woolliams, C, Wiener, G, Macleod, NSM (1983) The effects of breed, breeding system and other factors on lamb mortality: 2. Factors influencing the incidence of delayed birth, dystokia, congenital defects and miscellaneous causes of early death. The Journal of Agricultural Science 100, 553-561.

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