final report

Project code: L.LSM.0027

Prepared by:
Caroline Jacobson (Murdoch University)
Mieghan Bruce (Murdoch University)
Paul R. Kenyon (Massey University)
Amy Lockwood (Murdoch University)
David Miller (Murdoch University)
Gordon Refshauge (NSW Department of Primary Industries)
David G. Masters

Contributions from:
Andrew Thompson (Murdoch University)
John Young (Farming Systems Analysis Service)
Kevin Foster, Megan Ryan, Graeme Martin (University of WA)

Date published: April 2020

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

A Review of Maternal Dystocia

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

Executive summary

Lamb mortality is an important economic and welfare problem for the Australian sheep industry with 20 – 30% of lambs dying before weaning, 74% within three days of birth. A significant proportion of these lamb deaths and an unknown number of ewe deaths are related to dystocia (difficult birth). This review aims to describe the nutritional and non-nutritional pathways that may affect parturition and dystocia; quantify impacts on the Australian sheep industry, and; identify both opportunities to improve lamb and ewe survival and knowledge gaps requiring research and development.

Dystocia may originate from either the ewe (maternal dystocia) or lamb (fetal dystocia). The primary causes of maternal dystocia are fetopelvic disproportion, uterine inertia and failure of the cervix to fully dilate with fetal dystocia resulting from malpresentation, disease or congenital defects. Overseas studies indicate maternal dystocia accounts for 25-44% of dystocia cases.

Dystocia is categorised as A, B or C based on the presence of sub-cutaneous oedema, central nervous system lesion scores and whether lambs have walked, breathed and metabolised brown fat. The consequences include lambs that are born dead or with birth injury. Injured lambs are more susceptible to the confounding effects of starvation-mismothering and exposure in the first few days of life. This higher susceptibility of lambs born alive is related to behavioural and physiological anomalies in both lamb and ewe. Little is known of the longer-term impacts on ewes and lambs that survive dystocia.

Dystocia has been considered a problem for large single-born lambs. This is not universally correct as dystocia is a significant contributor to lamb deaths across all litter sizes. Optimal birthweight varies between breeds and birth types, with dystocia risk increased for lambs with very low or very high birthweight. Lower birthweight appears to be more of a risk for litter sizes greater than one. Ewes with low or high condition score in late pregnancy have a higher dystocia risk with fatter ewes the highest risk. Current recommendations for target weight and condition profile during pregnancy to manage dystocia risk are based on limited data, with optimum condition score to reduce dystocia risk likely to vary according to litter size. Dystocia rates have been reported to be higher for maiden ewes (especially when joined as ewe lambs) and ewes older than 4.5 years. The influence of ewe breed on dystocia risk is inconsistent between studies, but there may be scope to reduce dystocia risk using dam or sire selection following further studies.

There is limited potential to decrease dystocia through direct selection due to low heritabilites for dystocia categories (<0.1). There are dystocia indictor traits such as lambing ease, lamb size and conformation and yearling fleece and liveweight that are correlated to dystocia but some of these also have low heritability.

Maternal dystocia may be related to hormonal imbalances that impact dilation of the cervix or uterine contractions. Hormonal imbalances may be linked to endocrine disrupting compounds in the environment, including phytoestrogens produced by plants such as oestrogenic legumes and man-made xenoestrogens. Oestrogenic clovers are widespread in the moderate to high rainfall areas of southern Australia, and the contribution of these to dystocia may be significant. Management of periparturient ewes may also alter endocrine pathways, leading to dystocia. Hypocalcaemia, oxidative stress, and pregnancy toxaemia potentially may contribute to maternal dystocia, but these interactions have not been experimentally tested.

A systematic review of the literature identified that approximately 54% of lamb mortalities were associated with dystocia (including still births and perinatal deaths with evidence of hypoxic injury)

in Australian studies conducted since 1990. The proportion of lamb deaths attributable to dystocia was similar for lambs born to Merino and non-Merino ewes, although relatively few cases for non-Merino ewes are available. More data will be required to determine effects of ewe breed independent of other factors. The proportion of lamb deaths attributable to dystocia is higher for single lambs than twin lambs, but as total mortality is higher for twin-born lambs overall the number of twin lambs that die from dystocia is more than double that for singles.

Based on available evidence, it is estimated that approximately 6.9 million lamb deaths and 367,500 ewe deaths per year are attributable to dystocia in Australia for national flock of 42 million breeding ewes. The impact of dystocia on farm profit is sensitive to lamb sale price. Dystocia is estimated to reduce national farm profit by AU$616 million for dystocia-related lamb mortality and AU$56 million for ewe mortality based on an assumed lamb sale price of AU$6.50 per kg carcass weight. These estimates do not include reduced productivity for ewes and lambs that survive, cost of intervention, post-farmgate impacts along the supply chain or impact on community support and social licence.

A number of prospective mitigation strategies have been identified that have varying degree of evidence. These include, differential nutritional management of single and multiple bearing ewes, ram selection, avoiding mating of small or immature ewes, ensuring adequate mineral and vitamin status, managing mob size and providing edible shelter to reduce desertion and stress, providing appropriate supervision during lambing, minimising exposure to oestrogen pastures and other endocrine disrupting compounds, controlling predators and possibly culling susceptible ewes. These mitigation strategies may reduce the risk of dystocia related to fetopelvic disproportion, uterine motility, cervical dilation (ring womb), interruption of parturition and mortality of birth injured lambs

There are significant strategic and tactical knowledge gaps. This lack of knowledge means that while risk factors can be identified, there is limited evidence to support current recommendations. It is the recommendation from this review that research priorities focus on three key control points. These are: 1. The preparation of the ewe and developing fetus for birth and survival (Fitness to Lamb); 2. The stressors that directly influence the process of parturition and ability to recover from a difficult birth (Ready to Rear) and; 3. The within and between breed genetics that contribute to dystocia risk (Bred to Deliver).

To address the knowledge gaps and develop verified recommendations a staged approach is recommended. This would begin with an investigation and potential re-analysis of currently available datasets together with a national survey of producers. Depending on results from the initial steps a second stage of controlled field experiments, producer demonstration with aligned basic research is recommended.

1. Fitness to Lamb

Lamb birthweight, ewe maturity and liveweight, condition, condition profile and fatness, glycogen in uterine muscle and mineral status all influence the fitness of the ewe to give birth and lamb viability. There is currently insufficient information to provide tested recommendations to ensure fitness to lamb. The following research approach is recommended:

a. Investigation and possible re-analysis of existing datasets where fitness to lamb control points and dystocia have been measured or may be indicated;
b. Survey producers (particularly those with a history of dystocia) and collate information on measured risk factors and seasonal variation;
c. Field studies integrated with producer demonstration sites incorporating range of age groups, genotypes, years (seasonal variation) and environments to test and define ewe

and lamb condition, fatness and metabolic state required to minimise the risk of dystocia. Where possible consider add on to existing research;

d. Complementary basic research overlaying field studies to determine mechanisms associated with dystocia with focus on metabolic and hormonal changes that impact birth. To include studies/measurements on glycogen in uterine muscle and ewe aerobic fitness, sub-clinical hypocalcaemia, pregnancy toxaemia and oxidative stress. Consider support for PhD students

Progress to c. and d. dependant on results from a. and b., completion of d. with c. is likely to provide information that will support the extrapolation of results and reduce the years, environments and genotypes testing requirements.

Defining Fitness to Lamb was considered the highest priority for future research.

2. Ready to Rear

The short-term process of parturition and immediate recovery after difficult birth are closely related to stress and environment influences. The stress and reproductive hormones play a major role in the initiation and control of parturition and thermoregulation in the sheep, and these hormones are under both endogenous control and exogenous influence. As with Fitness to Lamb theme, there are knowledge gaps that limit the certainty of general recommendations. The following research approach is recommended:

a. Investigation and possible re-analysis of existing datasets where flock size, shelter and disturbance have been measured and possibly associated with dystocia;
b. Survey producers (particularly those with a history of dystocia) and collate information on stress and environmental conditions around parturition and time of lambing;
c. Field and producer demonstration studies to investigate flock size, supervision, shelter and weather conditions on the incidence of risk dystocia. Where possible consider add on to existing research;
d. Complementary overlay to field studies of basic research to include the relationship between hypoxia, hormonal change and thermoregulation in the lamb and the interactions between stress hormone changes and the parturition process;
e. Continued studies into the prevalence and consequences of oestrogenic pastures, with a particular focus on identification, measurement and eventually eradication.

3. **Bred to Deliver**

There is a genetic component to dystocia. This is at least partly explained by incompatibility in physical size and dimensions of the ram, ewe and lamb. The repeatability within a ewe is uncertain. There is also a heritable component although heritability of dystocia and indicator traits appears to be low. Positive correlations with some favourable production traits requires clarification. The following research approach is recommended:

a. Continued collection of genetic correlations between dystocia and production traits. Use within breeding indices where required. It is assumed this will be done as part of normal business by SGA;
b. As part of any field studies include breed, genotype comparisons of risk;
c. Investigate available data sets for evidence of repeatability.

Table of contents

Milestone description

Milestone 1: Submission of a milestone report detailing completion of:

1.1 Systematic review of evidence to determine reported incidence of dystocia in Australian sheep and estimated economic impacts

1.2 Review of available literature on factors contributing to maternal dystocia

Project objectives

This project will review available literature to:

1. Determine the rate and variation in rate of dystocia as related to breed, litter size and parity in the Australian sheep flock.
2. Estimate economic impact of ewe and lamb mortality, health and production associated with dystocia
3. Assess and interpret the physiological, endocrinological and biochemical changes associated with dystocia.
4. Assess and interpret the changes in maternal behaviour, milk production and myometrial activity associated with dystocia
5. Identify risk factors and opportunities to mitigate dystocia in Australian sheep production systems
6. Based on the reviewed information, identify gaps and propose new R&D priorities to reduce the impacts of dystocia on sheep production, health and welfare.

Success in meeting project milestones

	Milestone	Report reference	Status
1.1	Systematic review of evidence to determine reported incidence of dystocia in Australian sheep and estimated economic impacts	Section 6 of review	Complete
1.2	Review of available literature on factors contributing to maternal dystocia	Section 1, 2, 3, 4 and 5 of report	Complete
2.1	Submission of final report (a) collating outcomes from stage one and (b) identification of research gaps and R&D priorities to reduce ewe and lamb loss at parturition	(a) Sections 1-6 of report (b) Section 7 and 8 of report	Complete
2.2	Submission of a draft scientific journal manuscript for review (inclusive of estimate for rate and impact of dystocia for Australian sheep industry, and factors contributing to maternal dystocia)	1. Manuscript for Small Ruminant Research submitted for MLA approval 2. Manuscript for second article (systematic review and MIDAS modelling) fully drafted.	Complete
2.3	Published at least one article in communication/extension focussed publication	1. Article for Farming Ahead submitted to MLA for approval 23 April 2020 2. Content sent to Carly Mortimer (MLA) for Feedback Magazine 2 April 2020 3. Article for Ovine Observer submitted to MLA for approval 1 May 2020	Complete

A Review of Maternal Dystocia

1 Background

1.1 Pre-weaning mortality of lambs

The incidence of lamb mortality prior to weaning is high. Hinch and Brien (2014) summarised results from 15 Australian publications to conclude that, on average, 20 – 30% of lambs die before weaning and 74% of these deaths are within three days of birth. There was significant variation among locations and litter size, with mortality of single born lambs ranging from 6 to 30% and of twins from 19 to 63% (Geenty et al., 2014; Hinch and Brien, 2014). Others have reported lamb mortality rates from 10-25% in Australia, UK and New Zealand (Mellor and Stafford, 2004; Celi and Bush, 2010; Ferguson et al., 2014). It is likely that losses are similar in all other extensive sheep production systems including those in China and South America.

There has been little change in lamb mortality in recent years (Elliott et al., 2011). In Merino ewes the trend towards multiple births is associated with increased lamb mortality, however, there is evidence that with the appropriate selection index, genetic gains in both litter size and lamb survival are achievable (Atkins, 1980; Cloete et al., 2009; Brien et al., 2014) and in some maternal breeds there is little difference in survival between single and multiple born lambs (Conington et al., 2014). Differences in lamb mortality are associated with ewe age and parity, breed and genetics, maternal nutrition during pregnancy, birthweight, litter size, birth type, sex, weather conditions, and the physiological and immunological status of the lamb (Hinch and Brien, 2014). The major causes of perinatal mortality are dystocia (19 – 67%) and starvation-mismothering-exposure (SME; 30 – 48%) (Dennis, 1974; Holst et al., 2002; Refshauge et al., 2016). Dystocia is defined as a difficult birth due to a long, unassisted parturition or prolonged delivery requiring assistance (Arthur, 1975; Zaborski et al., 2009).

1.2 Ewe deaths during pregnancy

There is little information available on the incidence and cause of ewe deaths during pregnancy. Annual losses have been estimated at 2-10% in New Zealand and Australia, with higher susceptibility in multiple-bearing ewes (Trompf et al., 2011; McGrath et al., 2013b; Ferguson et al., 2014). The highest risk of ewe mortality is during the periparturient period but few data are available to support this expectation or to indicate the risks associated with dystocia.

1.3 Costs of perinatal lamb and periparturient ewe mortality

Neonatal mortalities have been estimated to cost the Australian sheep industry approximately AU$540.4 million each year with the dystocia component of the loss estimated at approximately AU$219 million (Lane et al., 2015). A 50% reduction in dystocia has been predicted to gain the industry approximately AU$77 million (Lane et al., 2015). These estimates do not account for possible production loss from surviving ewes and lambs in subsequent years. For ewes surviving dystocia, there are additional costs from impaired maternal instinct (Dwyer, 2014) and possibly dam fertility and stillbirths in subsequent pregnancies. The longer-term impacts on fertility and lamb-rearing are not well understood. For lambs surviving dystocia, there are also developmental

abnormalities along with reduced vigour and health (Smith, 1977; Dwyer, 2003; Dwyer and Bünger, 2012; Fonsêca et al., 2014).

1.4 Welfare considerations

Peri-natal lamb and periparturient ewe mortality not only have high costs associated with production losses but also present an animal welfare concern. There is an increasing demand for improved ethical and humane treatment of animals during the production process. Ferguson et al. (2014) summarised some of the consequences of these demands as:

- Increasing pressure to include welfare standards in trade agreements;
- Differentiation of products and brands based on animal welfare standards;
- Increased consumer pressure on governments to introduce a social license to operate;
- Products required to include welfare standards in provenance certification.

Failure to address and improve sheep welfare including ewe and fetal or lamb loss during and after pregnancy will compromise the brand, consumer trust and confidence, and may even threaten the licence to operate in some markets.

1.5 Aims of this review

The direct and indirect costs of dystocia are high and increasing. This review aims to identify the nutritional and non-nutritional stressors that affect parturition and dystocia in ewes. It will also re-assess the economic costs of dystocia. The review focuses on dystocia of maternal origin. Gaps in knowledge and prospective mitigation strategies will be identified for application and research.

2 Impact of dystocia on sheep survival, health and production

2.1 Maternal vs fetal dystocia

There are a number of underlying causes of dystocia that may originate from either the ewe (maternal dystocia) or lamb (fetal dystocia); (Table 1). The causes of maternal dystocia are inconsistent and vary between breeds. Cloete et al. (1998) observed the main cause of maternal dystocia was foetopelvic disproportion for South African Mutton Merino ewes and uterine inertia for Dormer ewes. Other studies have reported most maternal dystocia was caused by incomplete dilation of the cervix (Thomas, 1990; Sirinivas and Sreenu, 2009; Mostefai et al., 2019).

Fetal dystocia explains between 36% and 75% of dystocia cases, with most of these caused by malpresentation due to head deviation or limb flexion (Cloete et al., 1998; Sirinivas and Sreenu, 2009; Ennen et al., 2013; Mostefai et al., 2019).

Table 1: Causes of maternal and fetal dystocia

Maternal dystocia	Fetal dystocia
Fetopelvic disproportion	Malpresentation
Failure of the cervix to fully dilate (ringwomb)	Fetal disease and death
Vaginal prolapse	Congenital defects
Uterine torsion	
Inguinal hernia	
Uterine inertia	

2.1.1 Fetopelvic disproportion

Incompatibility between fetal size and the dimensions of the pelvis is a cause of dystocia that can occur over successive lambings (McSporran and Fielden, 1979). Fetopelvic disproportion is commonly associated with high lamb birthweight, with single-born fetuses at highest risk. Lamb conformation is also a consideration. Brown et al. (2014) analysed records for 3224 Merino or crossbred breed lambs born in Australia across four years. They reported some categories of death from dystocia were positively correlated with lamb thorax circumference adjusted for birthweight and negatively correlated with crown-rump length at a given birthweight. In contrast, the risk of birth injury was negatively correlated with thorax circumference and positively correlated with crown-rump length at a given birthweight. This indicates genetic selection for longer and thinner lambs may not reduce the incidence and consequences of dystocia (Brown et al., 2014). Congenital defects such as hydrocephalus, monsters, hydrops fetalis are uncommon in sheep, but may also present as fetopelvic disproportion (Jackson, 2004; Basher, 2006).

In ewes, the conjugate diameter of the pelvis and pelvic area is negatively correlated with the length of parturition and incidence of dystocia in many breeds (Fogarty and Thompson, 1974; McSporran and Fielden, 1979; Kilgour and Haughey, 1993; Cloete et al., 1998).

Strategies recommended to reduce the risk of fetopelvic disproportion include mating ewes at an age when they are adequately grown, ensuring ewes are not over-fat and careful sire selection (Ali, 2011; Brown et al., 2014).

2.1.2 Obstruction

Maternal dystocia due to obstruction of fetal delivery originating from the ewe can be due to ringwomb, vaginal prolapse, uterine torsion or inguinal hernia.

Ringwomb refers to inadequate softening and dilation of the cervix due to failure of normal physiological processes during parturition. Ringwomb is often reported as an important contributor to maternal dystocia outside Australia (Thomas, 1990; Sirinivas and Sreenu, 2009; Ennen et al., 2013; Mostefai et al., 2019). The incidence in Australian ewes is not well described but, for unexplained reasons, has been reported to vary between seasons (Jackson, 2004), indicating further research is required. Failure of cervical dilation may be observed in association with vaginal prolapse, cervical damage, uterine inertia or breech and other malpresentations of lambs (Jackson, 2004; Menzies, 2006).

Vaginal prolapse may occur before or at lambing due to increased abdominal pressure or reduced resistance of the reproductive tissues to distension. Predisposing factors include history of vaginal prolapse, increasing age and parity, larger litter sizes, poor nutrition, metabolic disease and prolonged recumbency with associated bladder distension (McLean, 1956).

Uterine torsion is uncommon in ewes, though may be confused with incomplete cervical dilation during clinical examination (Scott, 2011). Inguinal herniation of the uterus may also be associated with fetal obstruction but is uncommon in ewes (Sirinivas and Sreenu, 2009; Mostefai et al., 2019).

2.1.3 Uterine inertia

Uterine inertia is failure of the uterus to expel the fetus. Causes of uterine inertia may be categorised as primary inertia associated with disease impacting contractility or secondary inertia due to exhaustion with prolonged labour (Menzies, 2006).

Primary inertia results when uterine activity is reduced or disrupted in ewes with metabolic diseases such as hypocalcaemia and pregnancy toxaemia, endocrine disruption such as with consumption oestrogenic clover, or physical injury such as abdominal wall rupture, or hernia of the abdomen, umbilicus or perineum (Moule, 1961; Robalo Silva and Noakes, 1984; Jackson, 2004; Barbagianni et al., 2015). Uterine activity and progression of labour can also be inhibited by stress caused by disturbances during lambing which may predispose ewes to dystocia (Naaktgeboren, 1979).

Secondary uterine inertia due to myometrial exhaustion may be the consequence of prolonged labour, fetal malpresentation, loss of uterine tone or stress (Dwyer et al., 1996; Cloete et al., 1998). Overstretching of the myometrium or poor uterine tone following delivery of other fetuses may cause uterine inertia in multiple-bearing ewes (Jackson, 2004).

2.1.4 Malpresentation

Fetal dystocia due to malpresentation of lambs is associated with at least 50% of dystocia cases in studies based on requirement for intervention at parturition (Dwyer et al., 1996; Cloete et al., 1998). Common malpresentations include flexions of the neck, shoulder or carpus but dystocia may also result from breech presentation or simultaneous presentation of multiple-born lambs (Jackson,

2004). Congenital defects that result in arthrogryposis or monsters may result in malpresentation of the fetus.

2.1.5 Other causes of dystocia

Failure of the initiation of birth and subsequent dystocia may also result from fetal death *in utero* (Jackson, 2004). Unpublished data from the Australian Sheep Cooperative Research Centre Information Nucleus Flock indicate 30% of dead lambs categorised as premature or dead *in utero* required assistance in delivery (G Refshauge pers comm). Autolysis and emphysema of dead fetuses can compromise the uterus and increase the risk of vaginal or uterine damage during delivery (Menzies, 2006). Hight and Jury (1970) and Refshauge et al. (2016) reported approximately 10% of perinatal lamb deaths occurred *in utero*, however the incidence of dystocia associated with delivery of these fetuses is unknown. *In utero* death may be caused by compromised placental function, infection, exposure to toxic agents, metabolic disease, stress or congenital defects.

Uncommon causes of maternal dystocia include hydropsy and sciatic nerve paralysis impacting function of the hindquarters (Patil et al., 2014; Prasad et al., 2014).

2.2 Dystocia and lamb survival

2.2.1 Dystocia and birth injury in lambs

Dystocia predisposes lambs to birth injuries that impact viability. Prolonged parturition increases the risk of asphyxia. As many as 33% of newborns experience severe asphyxia and the risk of asphyxia is 15.6 times higher for twin-born lambs compared to singles (Dutra and Banchero, 2011). Hypoxia and acidaemia evident as haemorrhaging and congestion of the meninges of the brain, spinal cord and vertebral canal have been reported in dystocic deaths (Haughey, 1973b). More recently, Dutra et al. (2007) found that all autopsied lambs presented with hypoxic ischemic lesions of the central nervous system which indicated all dead lambs had experienced a lack of oxygen. However, it is not so simple to imply that a lamb which had not breathed will develop the lesions. The lesions are produced ante- or intra-partum, although forming post-partum lesions is not impossible if lungs fail to properly inflate. Apart from dystocia, lesions consistent with hypoxic injury may also be observed for lambs with intra-uterine growth restriction and delayed parturition (Dutra and Banchero, 2011).

Severity of these birth injury lesions is correlated with mortality risk (Haughey, 1980a, 1982), although the aetiology of birth injury in lambs is not well understood. Barlow et al. (1987) proposed that maternal contribution to neonatal lamb mortality through intrapartum asphyxia and reduced placental efficiency warrants further investigation. An experimental model of dystocia using peri-vaginal sutures to prolong duration of parturition in ewes demonstrated lamb mortality was 15% higher and the incidence of meningeal lesions were 9 times greater than controls delivered by caesarean birth (Haughey, 1982). This suggests that the vigour of birth and duration of labour both contribute to birth injuries. Increased neuronal death in the dentate gyrus of the hippocampus has been observed using immunohistochemical staining in lambs that died from of dystocia compared to lambs that died from starvation-mismothering-exposure or barbiturate overdose (Lashley et al., 2014).

2.2.2 Classification of dystocia and starvation-mismothering-exposure

The methodology used to identify cause of death attributable to dystocia at necropsy has evolved over the past 50 years. McFarlane (1965) identified the necropsy lesions used to determine time of lamb death in relation to the time of birth. These were subsequently characterised by Haughey (1973b, 1973c) and this system has since been widely adopted.

Holst (2004) refined this approach to categorise deaths associated with difficult birth into three categories. These were later modified by Refshauge et al. (2016) to include lambs with subcutaneous oedema that may have breathed or walked as Dystocia A (Table 2). The critical categorisation of lambs into one of the three classes of dystocia relies on the presence of significant oedema and central nervous system lesion scores. Based on this classification system, starvation-mismothering cases may have signs consistent with birth injury except for central nervous system lesions (Table 2). Other categories of death in this system are primary predation, prematurity or *in utero* death, primary exposure, infection, misadventure or undiagnosed (Holst, 2004). While this categorization is now well defined, the assessment of central nervous system lesion scores is subjective. Hence, the placement of lambs into the death categories relies heavily on assessor experience and bias. For example, lambs that die on cold days appear more likely be categorised into cold exposure whereas lambs that have been predated classified tend to be categorised into primary predation, irrespective of available evidence to suggest otherwise. Holst et al. (2002) found that most dead lambs had significant lesions of the brain tissues. Dutra et al. (2007) concluded that these lesions explain most deaths at birth and within 6 days of birth, despite categorising 49% of lambs to starvation-mismothering-predation and 40% to dystocia-stillbirth-birth injury. Other studies have reported that 20-60% of lambs categorised as SME also experienced birth stress apparent as central nervous system lesions (Alexander et al., 1980; Duff et al., 1982; Haughey, 1982; Haughey, 1983; Knight et al., 1988).

These studies indicate the complexity in differentiating both within dystocia categories and between dystocia and SME. Given the need for training and experience for the detection of lesions in dead lambs, published estimates of dystocia:SME are likely to underestimate the contribution of dystocia to lamb mortality.

Table 2: Methodology developed by Holst (2004) and refined by Refshauge et al. (2016) to classify lamb deaths associated with dystocia or starvation-mismothering

	Dystocia A (Holst, 2004)	**Dystocia A** (Refshauge et al., 2016)	**Dystocia B (stillbirth)**	**Dystocia C (birth injury)**	**Starvation-mismothering**
Oedema*	✓	✓	✗	✗	✗
Central nervous system lesion score **	≥2	≥2	≥3	≥3	<2 (no lesion)
Walked	✗	+/-	+/-	+/-	✓
Breathed	✗	+/-	+/-	✓	✓
Fat deposits metabolised***	✗	✗	✗	✓	✓

* subcutaneous oedema of head or shoulders

** Central nervous system (cranial, spinal) lesion score scale 1-5 (1 = no lesion; 5= severe haemorrhage, obvious blood clots & congestion)

*** Pericardial and perirenal fat deposits metabolised

2.2.3 Prospects for survival of lambs born alive

Long and difficult labours are associated with poorer ewe-lamb behaviour and lamb survival (Arnold and Morgan, 1975; Smith, 1977; Cloete et al., 1998; Dutra and Banchero, 2011). Ewes display a reduced frequency of low-pitched bleats, poorer grooming behaviours and an increase in rejection behaviour following a prolonged or difficult birth (Dwyer et al., 2003; Darwish and Ashmawy, 2011). Longer parturition has been associated with poorer lamb viability at birth, including latency to stand or suckle (Dwyer et al., 1996; Darwish and Ashmawy, 2011; Dutra and Banchero, 2011; Fonsêca et al., 2014), although this is not consistent in all studies (Duff et al., 1982). Slowed progress in righting movements, impaired suckling ability and depressed neonatal behaviours have been reported for lambs assisted at birth (Dwyer, 2003; Dwyer and Bünger, 2012). Lower suckling ability reduces access and absorption of colostral immunoglobulins (Hinch and Brien, 2014). Lambs with poor vigour in their first hour of life are less likely to survive (Murphy and Lindsay, 1996).

A reduction in energy and fluid intake in lambs with impaired suckling behaviours increases the vulnerability to wind chill when exposed to cold temperatures (Haughey, 1980a) and to dehydration during hot conditions. In addition to behavioural change in the lamb, depressed heat production associated with hypoxia or placental insufficiency further increases the risk of exposure or dehydration in cold or hot conditions (Haughey, 1980a; Eales et al., 1982). Depressed heat production may be evident soon after birth and persist for days for lambs with prolonged birth, with lower rectal temperatures before suckling and at 24 and 72 hours post-partum (Darwish and Ashmawy, 2011). Depressed heat production has been reported in association with severe hypoxia and acidaemia (Eales and Small, 1985), but the association between subacute hypoxia and heat production is not well understood. Susceptibility to hypoxia-induced hypothermia may be a direct result of placental insufficiency and chronic hypoxaemia (Mellor and Stafford, 2004). Impairment of heat production may only last for 0.5 to 1 hour after birth in cases of acute hypoxaemia following occlusion of the umbilical cord or prolonged birth (Eales and Small, 1985).

Sub-acute central nervous system injuries associated with dystocia are therefore not always fatal. However, the impacts on suckling, heat production and the ewe-lamb bond are often so challenging that the neonate is unable to survival without human intervention, particularly under cold or hot conditions. When kept disease free, warm and fed, very few hand reared lambs die and even very low birthweight lambs born following intrauterine growth restriction can be kept alive with intensive nursing care (Greenwood et al., 1998).

2.3 Dystocia and ewe health and survival

Most studies have focused on the impact of dystocia on survival of the lamb rather than ewes. Impacts on the ewe are usually attributable to trauma and haemorrhage during parturition, and septicaemia in the post-partum period (Mavrogianni and Brozos, 2008). However, there are relatively few studies that describe the incidence of complications or the consequences on ewe survival and production in extensive sheep production systems.

Trauma associated with dystocia and/or obstetrical intervention, including uterine rupture or tearing of the cervix, vagina, vulva or rectum, may result in severe haemorrhage, subsequent sepsis or organ

prolapse (Hindson and Winter, 2007; Roger, 2009). Dystocia also predisposes ewes to development of acute metritis. This may develop directly with unassisted dystocia or subsequent to conditions secondary to dystocia such as uterine or vaginal prolapse or retained placenta or fetal tissue, provision of obstetrical assistance or post-parturient ketosis (Tzora et al., 2002). Ewes with metritis may develop septicaemia and toxaemia which can result in death if untreated. Ewes often respond to treatment with an effective antimicrobial agent, oxytocin and non-steroid anti-inflammatories with no consequences to future fertility (Mavrogianni and Brozos, 2008; Roger, 2009). Good hygiene during lambing reduces the risk of metritis, especially where obstetrical assistance is provided.

The relationship between retained fetal membranes and metritis is not as clear for sheep as it is for cattle. Dystocia increases the risk of retained fetal membranes in ewes (Leontides et al., 2000).The risk of intrauterine bacterial colonisation is increased in ewes with retained fetal membranes (Tzora et al., 2002). However, this is not associated with impacts at subsequent lambing (Fthenakis, 2004).

Clostridial infections including *Clostridium chauvoei* (post-parturient gangrene) subsequent to trauma during parturition or obstetrical interference may progress to severe necrotizing myositis, toxaemia and death (Lewis, 2007; Roger, 2009). Vaccination of pregnant ewes and good hygiene during lambing reduces the risk of this condition.

2.4 Consequences for future production of surviving ewes and lambs

The 'carry-over' impacts of dystocia on the subsequent reproductive and productive performance of surviving ewes and lambs are not well studied. Haughey (1982) reported no permanent effect on growth or fleece production to two years of age following a prolonged or stressful birth. However, ewes with dystocia at their first lambing have a higher risk of dystocia at subsequent lambings. Lamb Ease score, a semi-quantitate score derived from the level of lambing difficult, recorded at maiden lambing can be used to identify ewes with increased risk of dystocia at subsequent lambings (Horton et al., 2018). However, the relationship between Lamb Ease score and dystocia at subsequent lambings is weak and other factors such as increased litter size play a more significant role (Horton et al., 2018).

Severe dystocia cases may be managed by caesarean delivery in valuable ewes. No differences in ewe mortality have been observed for caesarean compared to assisted deliveries (Waage and Wangensteen, 2009; Ennen et al., 2013). The impact of caesarean delivery on reproductive performance in the following season is variable, with several studies noting no consequences on conception and delivery (Mosdoel, 1987; Brounts et al., 2004) or no difference between caesarean and vaginal delivery for subsequent reproductive performance (El-Guindy and El-Ghannam, 1973). Others have noted that ewes that have previously undergone caesarean section typically give birth to smaller litters and a significantly higher proportion of stillborn lambs when compared to those that deliver vaginally (Waage and Wangensteen, 2013).

3 Physiological risk factors for dystocia

3.1 Litter size and birth weight

Dystocia has traditionally been considered as a problem caused by large single-born lambs. However, dystocia is a significant contributor to lamb deaths across all litter sizes (Holst et al., 2002; McHugh et al., 2016; Refshauge et al., 2016; Holmoy et al., 2017; Kenyon et al., 2019). Woolliams et al. (1983) reported higher rates of dystocia in singles than twins, although this difference was reduced when adjusted for birthweight. Others have confirmed this observation (Brown et al., 2014). While this does indicate that birthweight is a major driver of dystocia, it also indicates that other factors are involved. Fetal entanglement, malpresentation and prolonged birthing process are also major contributors to lamb dystocia deaths in multiple-born lambs (George, 1976; Woolliams et al., 1983; Hinch et al., 1986; Speijers et al., 2010; Dwyer and Bünger, 2012; Kenyon et al., 2019).

A quadratic relationship between birthweight and the risk of peri-parturient lamb death, irrespective of cause, is well established (Knight et al., 1988; Geenty et al., 2014). Although optimal birthweight varies between breeds and birth types, Australian studies using the Australian Sheep Cooperative Research Centre Information Nucleus Flock data set indicate that the risk of dystocia is lowest for lambs with birthweight between 4.5 and 5 kg (Brown et al., 2014; Horton et al., 2018). The quadratic relationship between survival and birthweight explained 70% of the variation in lamb survival (Geenty et al., 2014). Management of lamb birthweight to avoid dystocia is however problematic; the very large variation in birthweight (1.5 - 10 kg) observed by Geenty et al. (2014) were from lambs born to ewes that were similarly managed to targets of adequate body condition.

Consistent with the relationship between birthweight and periparturient mortality, analyses using the Australian Sheep Cooperative Research Centre Information Nucleus Flock data set demonstrated dystocia rates too are higher at the birthweight extremes in singles, twins and triplets (Brown et al., 2014; Horton et al., 2018). Everett-Hincks and Dodds (2008) observed in singles, twins and triplets that the risk of death due to dystocia increased as the birthweight of the individual lamb deviated from the mean for its birth type. Horton et al. (2018) divided dystocia into low and high birthweight dystocia and reported that the rate of low birthweight dystocia increased with litter size while high birthweight dystocia was not affected by litter size. Refshauge et al. (2016) also reported that lighter multiple-born lambs were more likely to display dystocia than lighter singles. Interestingly, Horton et al. (2018) reported that the optimum birthweight to minimise the risk of dystocia in singles may be lower than that for multiple-born lambs. Refshauge et al. (2016) reported that the risk of a lamb dying from birth injury increased as lamb body mass index increased. Combined, these findings indicate that there is an optimum range in birthweight for each birth type that will reduce the risk of dystocia. Understanding how to manipulate birthweight and variation in birthweight within a flock would be beneficial for reducing dystocia and possibly also other production parameters.

3.2 Ewe live weight and body condition score

The relationship between ewe liveweight or body condition and dystocia is inconsistent across studies. Hall et al. (1994) reported that ewe liveweight at joining had no influence on dystocia rates.

In contrast, Horton et al. (2018) reported positive relationships for both ewe liveweight and condition at joining with the risk of both low and high birthweight dystocia. Further, they reported a positive relationship for ewe liveweight at days 60 and 90 of pregnancy and the risk of both low and high birthweight dystocia.

Ewe liveweight change and condition score in late pregnancy may impact the risk of dystocia. Liveweight gain in the last six weeks of pregnancy was reported by Scales et al. (1986) to be positively associated with increased rates dystocia in singles but decreased rates in twins. However, ewe liveweight just prior to lambing had little effect on the proportion of ewes requiring assistance at lambing. Horton et al. (2018) found a positive relationship between ewe liveweight at day 120 of pregnancy and the risk of dystocia, though high condition score at day 120 of pregnancy was associated with a reduced risk of low birthweight dystocia and a tendency for lower rates of high birthweight dystocia. George (1976) reported that annual stocking rate, a proxy for individual ewe feed allowance, had no influence on dystocia rates in a year-round study.

Increased ewe body condition at lambing may impact dystocia risk. Holst et al. (2002) observed greater central nervous system lesion scores for offspring of fatter ewes, and concluded a 'dam fitness quotient' was present whereby ewes with high fat level were predisposed to dystocia and fetal birth injury. The mechanism by which dystocia and birth injury occurs in overconditioned ewes is not well understood, and whilst both heavy and light lambs are at risk of dystocia and birth injury, hormonal differences in lambs born to fatter ewes could be involved.

Loss of ewe body condition during pregnancy and low condition score at lambing is also a risk factor for dystocia. Behrendt et al. (2019) observed higher incidence of dystocia C (birth injury) and lower rectal temperature for lambs born to ewes managed to reach body condition score 2.4 or 2.8 at lambing compared to lambs born to ewes managed to reach body condition score 3.2 or 3.6.

It seems most likely that ewes with low or high condition score will be at a higher risk of dystocia. The optimum condition score for reduced risk of dystocia may vary between single- and multiple-bearing ewes. Drawing further conclusions is impeded by the limited numbers of studies. Therefore, further studies that link the risk of dystocia with ewe weight and condition profile during pregnancy and/or meta-analysis of existing data are required before firm conclusions and recommendations can be made (Horton et al., 2018).

3.3 Time of lambing

Time of lambing has implications for ewe nutrition and therefore ewe weight and condition score and lamb birthweight. Pregnant ewes predominantly graze in seasonal environments meaning that feed supply and pattern of availability will vary for different selected mating and lambing times. In southern Australia, lambing ranges from March to November (Croker et al., 2009). There are few studies which compare the risk of dystocia across different times of lambing. However, there is some evidence that variation in the availability of energy, protein, minerals and vitamins will influence the incidence and category of dystocia (Osuagwuh et al., 1980).

3.4 Ewe parity and age

The rate of dystocia and lamb birth injury have traditionally been reported to be highest in first parity ewes, with little or no difference between ewes of greater parity or age (George, 1976; Woolliams et al., 1983; Mathias-Davis HC et al., 2010; Speijers et al., 2010; McHugh et al., 2016; Refshauge et al., 2016). Li and Brown (2016) reported that lambing difficulty decreased with increase in age of the dam, but only up to 4.5 years. After this age, lambing difficulty increased. Horton et al (2018) reported that the incidence of dystocia increased with ewe age. However, older ewes with dystocia were predominantly triplet-bearing with low birth-weight lambs indicating that this increased risk was specific to low birthweight dystocia. Fetal entanglement may have been a contributing factor for dystocia in that cohort. The distribution of high birthweight dystocia was more even across ewe age groups (Horton et al., 2018).

Younger ewes have been reported to have a longer parturition and require more birthing assistance (Everett-Hincks et al., 2007; Matheson et al., 2012). Yearling ewes are approximately 60 -70% of their mature body weight and the increased incidence of dystocia is usually attributed to disproportion between the size of the ewe and lamb (McMillan, 1983). Parity and age are often confounded and therefore the explanation for higher dystocia rates in first parity ewes has been their smaller physical size. There is a positive relationship between ewe liveweight and pelvic diameter and increasing pelvic diameter has been associated with a lower incidence of dystocia and greater lamb survival (Knight et al., 1988; Kilgour and Haughey, 1993; Cloete, 1994).

McHugh et al. (2016) reported that birthing difficulty rates did not differ between first parity ewes lambing at approximately one or two years of age. The greater risk of dystocia in first parity ewes therefore cannot simply be explained by the physical size of the ewe and disproportion between maternal and fetal size. Redmer et al. (2004) reported that over-nourishing the pregnant adolescent ewe results in rapid maternal growth at the expense of the nutrient requirements of the gravid uterus. Subsequent nutrient deprivation to the feto-placental unit and uterus could impact on the normal mechanical and endocrine parturition processes.

3.5 Breed

The influence of breed on the risk of dystocia has been inconsistent between studies. Differences in the number and types of breeds compared in these studies is likely to explain a significant proportion of this variation. It is also important to acknowledge that there can be considerable variation within breeds for given traits.

Dam breed has been found to influence the rate of dystocia (Knight et al., 1988; Dawson et al., 2002; Kerslake et al., 2005; Dalton et al., 2012; Dwyer and Bünger, 2012; McHugh et al., 2016), possibly due to differences in pelvic size (Knight et al., 1988; Cloete et al., 1998; Dawson et al., 2002; Dalton et al., 2012). This is more likely to occur in breeds selected for terminal sire traits including muscling (Dwyer and Bünger, 2012; McHugh et al., 2016). However, ewe breed has not been found to affect the rate of dystocia in all studies (Woolliams et al., 1983; Geenty et al., 2014; Refshauge et al., 2016).

Speijers et al. (2010) reported that sire breed influenced the risk of dystocia risk. This was driven by variation in lamb birthweight and malpresentation of lambs between sire breeds. However, Geenty et al. (2014) reported inconsistent effects of sire breed on dystocia rates across a series of sites and farms. Others have reported no effect (Knight et al., 1988; Dawson et al., 2002; Refshauge et al., 2016).

Combined, these results suggest that there is scope for producers to manipulate the risk of dystocia through selection of dam and/or sire breed. However, further work is required to compare the risk of dystocia for different genotypes in given environments, before firm recommendations can be made to producers.

3.6 Sex of lamb.

Dystocia rates have been reported to be higher in male lambs (Everett-Hincks and Dodds, 2008; Mathias-Davis HC et al., 2010; McHugh et al., 2016). Further, male lambs have been reported to need more birthing assistance (Matheson et al., 2012). Male lambs are generally heavier than female lambs are birth which is likely to explain much of their greater risk of dystocia. However, McHugh et al. (2016) reported that the difference still existed after adjustment for birthweight, suggesting other factors also play a role in dystocia risk.

3.7 Summary

The physiological and environmental factors contributing to dystocia and the relative contributions to lamb mortality are summarised in Figure 1. This figure is based on an average lamb mortality of 20% and is at the lower end of the range reported by Hinch and Brien (2014). Estimates of lamb deaths and causes are therefore likely to be conservative.

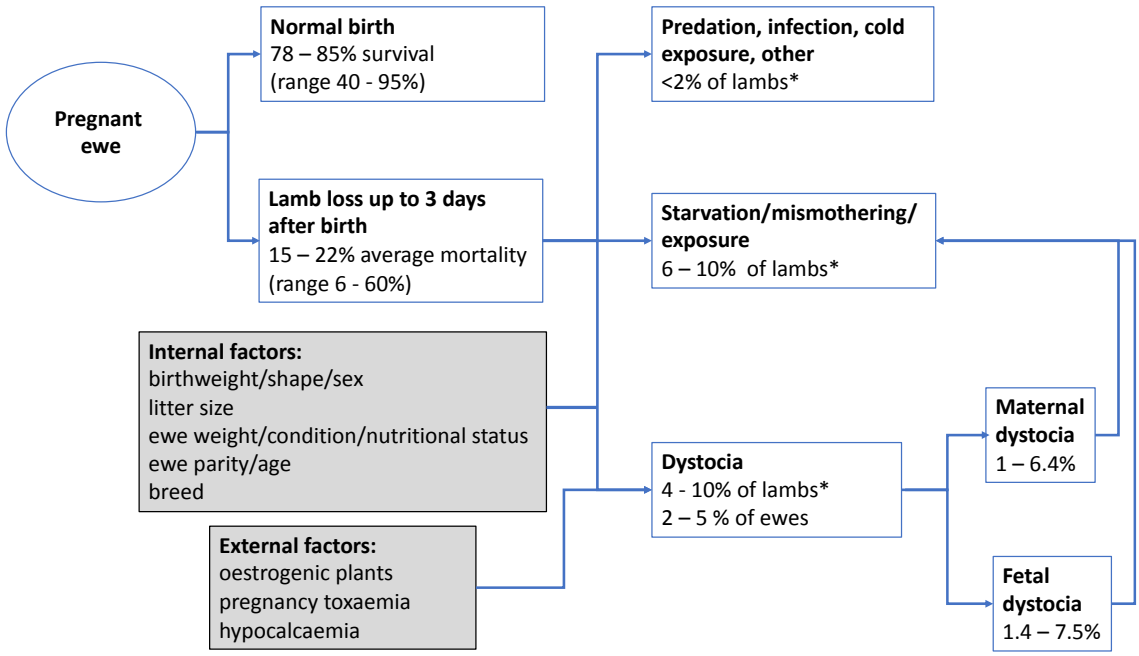

Figure 1 Schematic summary of lamb survival and dystocia in Australian sheep flocks

4 Genetic options for dystocia management

The pursuit for highly productive breeding stock has its compromises. Domestication and intensive selection has led to a longer parturition and less favourable maternal behaviours, when compared to breeds that experience little human intervention (Dwyer and Lawrence, 2005). Selection for accelerated growth rate, increased muscling, optimal fat coverage, the use of larger sires and the retention of assisted lambs may be contributing to more difficult parturitions and reduced lamb vigour (Speijers et al., 2010; Dwyer and Bünger, 2012). Further examination of the relationship between lamb conformation and dystocia is warranted because in some cases extra muscling around the neck and shorter neck bones may be advantageous during birth (Dutra et al., 2007).

Unfavourable genetic correlations between production traits and perinatal lamb mortality have been reported. Yearling greasy fleece weight has a positive genetic correlation with Dystocia A, B and C, while yearling weight has a positive genetic correlation with Dystocia A and C (Brown et al., 2014). This suggests that selection for fleece and yearling weight alone may result in higher rates of dystocia.

There is limited potential for a rapid reduction in dystocia through direct genetic selection. Heritabilities for some categories of dystocia (including still birth and birth injury) and lamb survival range from 0.02 to 0.04, with a moderate level of genetic correlation between dystocia types (Brien et al., 2010; Brown et al., 2014). This is consistent with observations of Everett-Hincks et al. (2014) who also reported low heritabilities for dystocia (0.01 to 0.07) in a large study in New Zealand. Matheson et al. (2012) determined the heritability of birthing assistance to be 0.26 and reported genetic correlations with lamb vigour and the need of suckling assistance of 0.68 and 0.54 respectively.

Dystocia indicator traits include lambing ease (Lamb Ease score), lamb thorax circumference, lamb crown rump length and yearling fleece and birthweight. Of these, lambing ease has the highest genetic correlation with dystocia of up to 0.45 followed by lamb thorax circumference of up to 0.44 which indicates that these traits could be used in selection programs to reduce dystocia rates (Brown et al., 2014). These correlations indicate that it may be possible to select against dystocia using the indicator traits including lambing ease and lamb size, weight and conformation at birth, combined with other lamb survival and ewe rearing ability traits. Everett-Hincks et al. (2014) reported a moderate level of heritability for the indicator trait of lamb birth-weight (0.32 to 0.43) while Brien et al. (2010) reported a low heritability of 0.09 for lamb ease. Li and Brown (2016) reported a low genetic correlation between lamb ease and birth weight (0.31) and between lamb ease and gestation length (0.24).

Horton et al. (2018) found that prediction of future dystocia from previous dystocia was not reliable. Furthermore, they observed that the repeatability of low and high birthweight dystocia was not consistent. However, the authors suggested that a small proportion of ewes could be identified as high risk and managed differently from the rest of the flock.

In cattle, positive correlations are found between heifer body height, hip height and shoulder height with calf birth weight (Basarab et al., 1993) indicating that larger heifers with a larger pelvic inlet give birth to correspondingly larger calves (Zaborski et al., 2009). In studying 14 cattle breeds, Laster (1974) found heavier cows have calves with greater weight deviation from the mean and were

tending to have larger pelvic area. Selection to increase pelvic size relative to calf birth weight or pelvic size relative to cow body weight should lead to favourable reductions in dystocia (Taylor et al., 1975). Albeit with high standard errors, Morrison et al. (1986) estimated a genetic correlation between pelvic area and cows weight at 0.57, similar to those by Upton and Bunter (1995) with liveweight (0.5-0.6) and with hip height (0.53-0.71), while Meyer et al. (2010) reported correlations to hip height at 0.21-0.44. Calf birth weight is however, strongly correlated with pelvic area at 0.73-0.75 (Benyshek and Little, 1982; Cook et al., 1993), suggesting that selection for reduced birth weight will see concomitant reductions in progeny pelvic area. Pelvic height and area are positively correlated with body weight in Angus and Hereford dams, with larger dams found to have greater pelvic dimensions (Bellows et al., 1971).

5 Endocrine, nutritional and metabolic relationships with birth and dystocia

The length of gestation is tightly regulated and is determined by fetal genotype. The ewe generally does no more than expressing her preference for giving birth at a suitable birth site or at a particular time of day. During the gestational period the fetus undergoes the growth and developmental changes that will allow it to successfully transition from an intrauterine to extrauterine existence at parturition. The dominant hormone during gestation in sheep is progesterone secreted by the placenta. It is often called the "hormone of pregnancy" as it has many roles relating to the development of the fetus (Liggins, 1982). One of these roles is to block uterine myometrial activity to prevent early expulsion of the fetus (Heap and Flint, 1984). Hence, the needed increase in contractility of the myometrium at parturition to expel the fetus necessitates the removal of this hormonal inhibition. The way that progesterone dominance is removed, at least in the sheep, is an example of how placental endocrine function is influenced by the near-term fetus.

5.1 Parturition – the neurohormonal cascade

The chain of events leading to parturition begin with biochemical connective tissue changes in the cervix which precede uterine contractions that, in turn, lead to cervical dilatation to allow expulsion of the fetus. The fetus is crucial in this process as it initiates a neurohormonal cascade, via activation of the fetal hypothalamic-pituitary-adrenal (HPA) axis, which sets in motion the physiological, endocrine and biochemical changes needed (Fowden et al., 1998). Appropriate and timely cervical remodelling and uterine contractions are key for successful birth. It has been suggested that hormonal imbalances related to activation of the fetal HPA axis may result in dystocia, commonly presenting as the cervix not being completely dilated or the uterine contractions being affected (Braun, 2007).

5.2 Role of the fetus

Toward the end of gestation, and at the onset of parturition, there is an increase in fetal plasma corticosteroid concentration due to maturation and sustained activation of the fetal HPA axis (Fowden et al., 1998). The chronological timing of this has a strong genetic component (Kitts et al., 1984; Kitts et al., 1985), but can be modulated to some extent by internal and external factors (Clegg, 1959). For example, Forbes (1967) showed that gestation length was influenced by the lamb birth type, size and sex and the age and nutrition of the ewe , albeit by only about 2% (i.e. 2 – 3 days). In the 1960s investigators also became aware that ingestion of certain teratogenic shrubs by sheep predisposed them to prolongation of gestation (Coppock and Dziwenka, 2017). Morris (1973) and Holst et al. (1986) also found that over-feeding during certain 'windows' of gestation increased gestation length, but again only by a few days. Prolonged gestation could increase the risk of

dystocia due to fetal overgrowth. However, there is little direct evidence for this in sheep, perhaps due to the subtle nature of the length of gestation effects seen in the above studies.

A general characteristic of fetal endocrine maturation across different species is the enhanced activity of the fetal HPA axis during late gestation (Challis et al., 2001). Activation of this axis has been linked to a changing intra-uterine environment, such as hypoxemia (Braems et al., 1996) which would act as a stressor to the fetus. HPA development is associated with increased levels of adrenocorticotropic hormone (ACTH) and adrenal corticosteroids (cortisol in sheep) in the fetal circulation (Challis and Olsen, 1988), and increased corticotrophin releasing hormone (CRH) synthesis in the hypothalamus (Challis, 1995). At term, increased levels of cortisol act on the placenta to increase expression of prostaglandin (PG) synthase (Challis, 2013). Increased synthesis of PG in turn increases the activity of enzymes in the fetal membranes that result in increased local generation of cortisol from cortisone, with further paracrine/autocrine stimulation of PG output (Challis, 2013). Increased fetal cortisol contributes to the maturation of organ systems, such as the lungs, required for post-natal survival of the lamb in the extra-uterine environment (Challis and Olsen, 1988), and starts the cascade of events leading to parturition. Thus, the level of fetal HPA activity is crucial not only for determining gestation length, but also in preparing the fetus for extra-uterine life. There has been minimal investigation on the effect of altered fetal HPA activity impacts the risk of dystocia in sheep.

5.3 Role of the placenta

Cortisol from the fetal adrenal gland provides the signal for the subsequent maternal endocrine changes. In sheep this is primarily driven by changes in the hormonal output of the placenta (Flint et al., 1975). During gestation, the myometrium is rendered quiescent under placental progesterone dominance via refractoriness to stimulation by PG-F2alpha and oxytocin. Removal of progesterone dominance is essential to start the cascade of events leading to birth.

The mechanisms by which increased concentrations of cortisol in the fetal circulation drive the subsequent hormonal changes that initiate the onset of parturition in the sheep have been reviewed previously (Challis and Brooks, 1989; Liggins and Thorburn, 1994). The increase in fetal cortisol prior to parturition causes an increase in the activity of the enzyme P450 C17 in the placenta. As a result, C21 steroids reaching the placenta can be metabolized to C19 steroids and then another placenta enzyme, P450 aromatase, converts the C19 steroids to oestrogen. The prepartum increase in oestrogen results in increased output of PG-F2α from the placenta which in turn acts on uterine tissues (Challis et al., 2001). More recently it has been proposed that fetal cortisol may also act directly on placental tissue to stimulate PG secretion (Challis, 2013), particularly PG-E2. It has been shown that PG-E2 has a primary role in the regulation of cervical softening and dilation at term (Ledgert et al., 1983; Owiny and Fitzpatrick, 1990). Braun (2007) suggested that hormonal imbalances could result in dystocia due to the cervix not being completely dilated. This may occur via alteration of placental PG-E2 actions, although this has not been investigated.

5.4 Role of the ewe

Two changes must take place in a ewe's reproductive tract for parturition to occur. First, the uterus must be converted from a quiescent structure to a contracting organ. This requires the formation of gap junctions between myometrial cells to allow for transmission of the contractile signal. The second change is that the cervical connective tissue and smooth muscle must be capable of dilatation to allow the passage of the fetus from the uterus. Myometrial activity becomes synchronised and uterine contractions increase in both frequency and amplitude just before the time of parturition (Liggins, 1982). With the fetus now being pushed onto and through the cervix there is a neurohormonal reflex release of oxytocin from the maternal pituitary gland, which further increases the contractions and leads to the expulsion stage of parturition (Heap and Flint, 1984). All of these changes are accompanied by a shift from progesterone to oestrogen dominance (Heap et al., 1977), increased responsiveness to oxytocin by means of up regulation of myometrial oxytocin receptors, increased PG synthesis by the uterus (Jenkin, 1992), increased myometrial gap junction formation (Garfield et al., 1979), decreased nitric oxide activity and increased influx of calcium into myocytes leading to increased myometrial activity (Crankshaw et al., 1979; Massmann et al., 1999).

5.5 Endocrine changes associated with dystocia

As mentioned above, hormonal imbalances may result in maternal dystocia commonly presenting as the cervix not being completely dilated or the uterine contractions being affected (Braun, 2007). Most commonly dystocia associated with hormonal imbalances is linked to endocrine disrupting compounds (EDC) in the environment. The main EDCs are xenoestrogens and phytoestrogens. Xenoestrogens are man-made synthetic products whereas phytoestrogens are derived from plants. Although there is less evidence, it is also important to consider the role of animal management in altering endocrine pathways leading to dystocia.

5.5.1 Oestrogenic pastures

Phytoestrogens, polyphenolic compounds, are one of the major plant secondary metabolites found abundantly in animal diets. Many forage legumes contain oestrogenic compounds that cause infertility in grazing animals. The richest sources of phytoestrogens in sheep diets is clover, but other legumes such as medics (including Lucerne) are a risk. This risk is primarily from green clover plants but may also occur in dry or rank medics under fungal attack (K Foster pers comm). The putative effects of phytoestrogens are based on their structural similarity to the mammalian oestrogen, 17β-oestradiol, and thus their potency to bind with mammalian oestrogen receptors. More attention has been paid to these metabolites since they can act as oestrogen agonists or antagonists (Usui et al., 2002), which makes their effects variable. The oestrogenic activity of phytoestrogens depends on many factors such as chemical structure of the compound, bioavailability, responsive tissue and its oestrogen receptor sub-type (ERα or ERβ), and metabolites resulting from their fermentation and digestion (Shutt and Cox, 1972; Lundh, 1995).

It is expected that phytoestrogens can alter reproduction of females on different levels because endogenous oestrogen receptors are widely distributed in the entire reproductive axis (hypothalamus, pituitary, ovary and reproductive tract).

Phytoestrogens generally inhibit endogenous oestrogens production, leading to disturbances in the follicular development and lack of the occurrence of oestrus (Rosselli et al., 2000). Further, it has been suggested that phytoestrogen compounds may disturb oestrus and ovulation through their effects on the central nervous system (Wocławek-Potocka et al., 2013).

It has long been known that high levels of oestrogens found in older varieties of subterranean clover (*Trifolium subterraneum* L) can interfere with sheep reproduction, with the effects often referred to as 'clover disease'. Bennetts et al. (1946) first described severe clinical symptoms in sheep grazed on highly oestrogenic clover pastures that included ewe infertility, prolapsed uteri, dystocia and increased lamb mortality. Ewes grazing oestrogenic varieties of subterranean clover have reportedly had rates of dystocia of 40%, with 20% ewe mortality and 60% mortality of lambs born (Moule, 1961). Davies et al. (1970) also reported higher mortality of lambs born to ewes grazing highly oestrogenic varieties (30–47%) compared with other varieties with a lower oestrogen concentration (16 to 30%).

Oestrogenic clovers are still widespread in the moderate to high rainfall areas of southern Australia. This is not surprising, a recent survey indicated 70% of producers have not re-sown a paddock to one of the newer varieties in the last 25 years, so the probability of pastures containing high levels of oestrogenic clover is very high (Foster et al., 2019). Adams (1995) estimated that approximately four million ewes are affected in south Western Australia. In 2002 it was reported that between 10 – 15 million sheep in the national flock were possibly being affected to varying degrees by oestrogenic clovers (Walker et al., 2002). This number is still applicable to the current flock, with a recent survey in Western Australia, South Australia, New South Wales and Victoria indicating 25% of pastures collected contained potentially potent concentrations of phytoestrogens (Foster et al., 2019) with the figure being over 65% in some districts. Clover disease remains one of the most significant environmental factors in poor ewe reproductive performance in southern Australia.

The pathogenesis of clover-induced dystocia is not well understood. Bennetts et al. (1946) suggested that dystocia resulted from primary uterine inertia. However, Maxwell (1970) and Adams and Nairn (1983) suspected that some outbreaks of dystocia resulted from failure of the cervix or vulva to dilate. Treatment of ewes with diethylstilbestrol, a synthetic oestrogen, can produce a syndrome in which the expulsive effort of the uterine musculature is normal but the cervix or vulva fails to dilate (Clark, 1965; Hindson et al., 1968), in a fashion similar to the dystocia ascribed to phytoestrogens. However, the effect of phytoestrogens may not be direct because treatment of ewes with oestrogen in late gestation does not result in dystocia (Clark, 1965). It is possible that the condition arises from a refractoriness of the genital tract to oestrogenic stimulation. If, for example, the ability of oestrogen to induce the synthesis of PG were impaired, both uterine motility and dilation of the cervix could be impeded (Anderson et al., 1981). Woclawek-Potocka et al. (2005) found that soy-bean (*Glycine max* L) derived phytoestrogens altered the production of luteolytic PGF2a in cattle during the oestrous cycle and early pregnancy. The effect of phytoestrogens on uterine and cervical function during parturition have not been investigated. Further investigations into the pathophysiology of the effects of oestrogenic clover on the occurrence of dystocia are warranted.

5.5.2 Endocrine disrupting compounds.

EDCs “interfere with the synthesis, secretion, transport, binding, action, or elimination of natural hormones in the body that are responsible for the development, behaviour, fertility and maintenance of homeostasis” (Crisp et al., 1998). Animal exposure to EDCs can occur via ingestion of food, dust and water, inhalation of gases and particles in the air and through the skin. EDCs can also be transferred from pregnant sheep to developing fetus or to the lamb through the milk. The most abundant EDCs in the environment are the xenoestrogens. Xenoestrogens are oestrogen-mimicking compounds which are not produced by the animal’s body. These compounds are structurally or functionally related to 17β-estradiol (E2) and bind the estrogen receptors (ERs) with various degrees of affinity and selectivity (Paterni et al., 2017).

Although there is no direct evidence for a link between EDCs and dystocia, several studies have indicated that EDCs can disrupt uterine structure and/or function in animal models (Gore et al., 2015; Feng et al., 2016). Moreover, EDCs like dioxins, polychlorinated biphenyls (PCB) and organochlorine pesticides, have been used extensively in agriculture, and due to their long half-lives remain persistent in the environment. In the UK, defects in fetal development were noted when pregnant ewes were exposed to a mix of EDCs contained in human sewage sludge, following its application to pasture as a fertiliser(Paul et al., 2005; Fowler et al., 2008).

5.5.3 Environmental and management stress and interruption during parturition

Environmental disturbances causing fright or anxiety may lead to two different effects upon uterine motility in many mammalian species, either inhibitory or excitatory. Stress causes an arousal of the sympathetic nervous system, leading to a release of adrenaline and other catecholamines, and glucocorticoids such as cortisol (Selye, 1956; Naaktgeboren and Slijper, 1970; Naaktgeboren and Bontekoe, 1976). From *in vitro* studies it has become clear that adrenaline is able to either excite or to inhibit uterine activity (Rüsse, 1963; Naaktgeboren and Slijper, 1970; Naaktgeboren and Bontekoe, 1976). However, little is known about the impact of environmental stress on the incidence of dystocia in sheep. One study investigating the underlying endocrine mechanism found that both stress (psychological) and exogenous adrenaline inhibited uterine motility in sheep, but only when endogenous plasma levels of oestrogen were high (Bontekoe et al., 1977). It is known in many species that adrenaline inhibits oxytocin release during the milk-ejection neurohormonal reflex during lactation (Whittlestone, 1954; Barowicz, 1979; Bruckmaier et al., 1997). However, the effect of stress (adrenaline) on oxytocin release during parturition and the role this plays in dystocia in sheep is less clear. The responsiveness of the HPA axis to stressors has been shown to be progressively attenuated during late pregnancy (Neumann et al., 1998; De Weerth and Buitelaar, 2005), and remains suppressed during parturition in other species (Gilbert et al., 1997; Douglas et al., 2003).

There is an established link between cold stress and lamb survival (McCutcheon et al., 1981). Challenges that threaten energy homeostasis, such as cold exposure, will normally lead to activation of the HPA axis resulting in the release of adrenal hormones which facilitate the mobilisation of energy substrates and supports energy homeostasis. These endocrine changes could interfere with parturition. Verbeek et al. (2012) reported that thin ewes with restricted feed intake had reduced

stress responses to an acute cold challenge, suggesting that the ewes had an impaired ability to temporarily adjust their physiology to the cold challenge. The possibility of heat stress impacting on fetal development and parturition should also be considered with climate change. Sustained heat stress in sheep during late gestation appears to be associated with intra-uterine growth restriction (Alexander and Williams, 1971; Brown et al., 1977), which may lead to fetal dystocia due to developmental abnormalities. Heat stress does not appear to alter the duration of parturition for ewes (Stephenson et al., 1984), though research in this area is limited.

Much more is known about the impacts of environmental and management stress on dystocia in dairy cattle. This has been reviewed by Mee (2008). Incomplete dilatation of the cow's cervix and vulva is more common when there is environmental stress or premature assistance during the periparturient period. Also, the increased risk of vulval stenosis and dystocia in heifers calving in stalls compared to pens or paddocks has been attributed to parturient stress and adrenalin and cortisol release. Moving heifers or cows during the early stages of calving is associated with increased risk of both dystocia. Assistance at calving before the cervix and vulva are fully dilated can result in iatrogenic dystocia due to cervico-vulval stenosis. Providing assistance less than one hour after the fetal hooves appear increases the risk of dystocia and reduced perinatal vigour, while delaying assistance for more than two hours prolongs calving and induces hyperlactataemia. Environmental disturbances at calving caused by the continuous presence of an observer, confinement, or overcrowded calving accommodation can lead to reduced uterine motility, cervical dilatation and abdominal contractions with resultant prolonged calving and dystocia. The effects of many of these environmental and management stressors on dystocia in sheep are either unknown or anecdotal.

5.6 Energy and protein

Energy and protein intake may influence the size of the lamb, the length of gestation, condition of the pregnant ewe and plays a direct role in the process of parturition. Maternal nutrition controls growth and development of the sheep fetus through nutrient partitioning and indirect metabolic effects (Redmer et al., 2004)). The effects of nutrient manipulation during pregnancy on fetal development and gestation length in sheep are subtle and inconsistent (Morris, 1973; Holst et al., 1986; Redmer et al., 2004), and may depend on the level and length of manipulation as well as the stage of pregnancy. Under-feeding sheep during late gestation is associated with intra-uterine growth restriction (Oliver et al., 2001). This is not likely to impact on maternal dystocia but the growth retardation may impinge on fetal dystocia through negative effects on development. The hypoglycemia associated with underfeeding the pregnant ewe shortens gestation length (West, 1996), though reversing this by experimentally inducing a state of hyperglycaemia does not always extend gestation length (Stevens et al., 1990). There is some evidence that over-feeding slightly increases gestation length. Longer gestation may be associated with dystocia (Morris, 1973; Holst et al., 1986; Redmer et al., 2004). Holst et al. (2002) found that lamb survival was negatively correlated with the fatness of the ewe and, in beef cattle, maternal obesity has been linked to dystocia (Arnett et al., 1971). Though, separation from the effects of fetal overgrowth have not been established.

Energy is also associated with the parturition process as it is required for muscle contraction. The specific energy expended during labour and parturition is not high relative to daily energy requirements (0.8 – 1.2 MJ) (Brockway et al., 1963) but, in other species, glycogen in the myometrium increases dramatically just prior to parturition and decreases significantly during birth . This indicates that glycogen may serve as an important energy source for uterine contraction (Chew and Rinard, 1979). Exogenous oestrogen also increases glycogen in the uterus (Bitman et al., 1967), so the increase in glycogen close to parturition is aligned with the change in the ewe from progesterone to oestrogen dominance.

There is also some evidence of interactions between nutrition and endocrinology that may influence the process of parturition. McMillen et al. (1995) suggested hypoglycaemia in the fetus may result in increased production of ACTH and cortisol and thereby play a role in the initiation of the HPA cascade. Others have postulated that progesterone stored in adipose tissue of overfat ewes may cause a hormonal imbalance at parturition leading to a dysfunctional birth process. This has not been tested experimentally (Holst et al., 2002).

Providing supplements which increase glucose supply, such as cracked maize, has been shown to increase colostrum production and may improve survival of lambs after a difficult birth (Banchero et al., 2004). These supplements were also associated with lower plasma progesterone in the ewe.

5.7 Minerals and vitamins

5.7.1 Macrominerals, vitamins and uterine activity.

Acute hypocalcaemia has been observed in ruminants for 200 years and, if untreated, may result in mortality of the pregnant ewe and fetus. Transient acute or subclinical hypocalcaemia is less well understood but has implications for the birth process and maternal dystocia. In the uterus, myometrial contractions are triggered by a rise in intracellular calcium (Ca) caused by an influx of Ca from extracellular space and mobilisation of intracellular Ca (Tribe, 2001). Low Ca allows sodium (Na) to enter the nerve cells, increasing irritability and causing spontaneous contractions and fasciculations (Friend et al., 2020). Secondary or subclinical hypocalcaemia increases dystocia, retained placenta and uterine prolapse in dairy cattle (Curtis et al., 1983; Risco et al., 1984). Less is known of secondary effects in the ewe. Older ewes are more susceptible to hypocalcaemia in commercial production systems and incidence hypocalcaemia increases from about 6 weeks prior to lambing. Hypocalcaemia in cattle is usually observed later in pregnancy and early lactation and may therefore coincide with parturition. Although hypocalcaemia is less likely to coincide with parturition in the ewe, induction of hypocalcaemia by infusion of the disodium salt of ethylene-diamine tetra acetic acid results in a reduction in uterine activity (Silva and Noakes, 1984), indicating a likely relationship between Ca and dystocia in sheep. In field studies, Caple et al. (1988) reported subclinical hypocalcaemia in ewes was associated with lower lamb survival.

Hypocalcaemia is primarily due to a failure of the endocrine system to respond to increased demand for Ca. There is uncertainty around the role of mineral and vitamin intake in mitigating the susceptibility in ewes (Friend et al., 2020). Modern pastures grazed around parturition often provide an imbalanced supply of Ca, magnesium (Mg), potassium (K), phosphorus (P), Na, vitamin D and

dietary cation-anion difference (DCAD) (Masters, 2018; Masters et al., 2019). High K and low Na in pastures depress absorption of Mg and may induce hypomagnesaemia, while low Mg, vitamin D and high P and DCAD will decrease Ca absorption or mobilisation. Hypomagnesaemia predisposes the grazing ruminant to hypocalcaemia (Herd, 1965).

Further studies are required to determine if mineral imbalance induces subclinical hypocalcaemia during late pregnancy and whether this subclinical hypocalcaemia causes uterine inertia and maternal dystocia in grazing ewes. If so, can the problem be managed through nutritional management?

5.7.2 Oxidative stress and maternal dystocia.

Dystocia is associated with acute inflammation of the uterus and cervix that leads to oxidative stress. Cytokine production and reactive oxygen species (ROS) in serum increase significantly at this time (Rizzo et al., 2008). Change from anaerobic to aerobic respiration also increases the production of ROS in the neonate ROS and if untreated, this may cause pathological conditions, disease or death (Mutinati et al., 2014). A direct relationship between oxidative stress and impaired uterine contractility has also been suggested in the ewe (Celi, 2010). Selenium (Se), manganese (Mn), zinc (Zn), copper (Cu), sulfur (S), vitamin E and vitamin A function synergistically in a series of antioxidant reactions that provide a defence against ROS (Masters, 2018). An imbalanced supply of these minerals and vitamins may slow recovery or compromise survival and long-term production. Moreover, magnesium sulfate has been shown to act as a neuro protectant through reduction in the production of cytokines and free radicals following hypoxia-ischemia (Marret et al., 2007; Plush et al., 2016), similarly caffeine may reduce the effects of hypoxia and has been associated with improved lamb survival (Robertson et al., 2017).

While there is insufficient evidence to indicate a lack of antioxidants is a primary contributor to the high rates of dystocia in ewes and subsequent production loss, there is evidence to support a strategy ensuring reproducing ewes have an adequate and balanced supply of antioxidants during the periparturient period, particularly when lambing on rapidly growing pastures in regions with a history of Se deficiency.

5.7.3 Indirect roles for minerals and vitamins in maternal dystocia.

Any vitamin or mineral deficiency that causes a loss in body condition or energy mobilisation may indirectly influence the birth process and potentially cause or accentuate maternal dystocia. Under commercial conditions deficiencies of P, cobalt (Co), Se and Cu can all cause weight loss (Suttle, 2010) while, in peri-parturient dairy cows a relationship between serum Ca and energy metabolites indicates that Ca may influence energy mobilisation and utilisation around parturition (Lean et al., 2014). A lack of iodine will increase susceptibility to cold stress in lambs surviving dystocia (Suttle, 2010).

5.8 Toxins

A wide variety of toxins have been demonstrated to have teratogenic effects that impact embryo survival and can be associated with congenital defects and malformation of the fetus. However, there is scarce information on the impacts of toxins on parturition for an otherwise normal fetus.

Ergopeptine alkaloids from ergot or grazing of fescue pasture infected with endophytes during late gestation can be associated with prolonged gestation, dystocia, agalactia and foal dysmaturity in horses (Porter and Thompson, 1992; Evans et al., 2004; Coppock and Jacobsen, 2009). Dystocia is not reported in sheep and sheep are generally less susceptible to endophyte toxicosis than cattle.

The pesticide carbaryl has been shown to have teratogenic effects via stillbirths and malformations in pigs and dogs, and dystocia associated with uterine atony has been observed in bitches exposed during pregnancy (Smalley et al., 1968). Carbaryl exposure is unlikely to explain dystocia in Australian sheep except in circumstances where ewes are grazing treated pasture during late gestation.

Scorpion venom exposure in late pregnancy can cause abortion or dynamic dystocia (Ben Nasr et al., 2007a; Ben Nasr et al., 2007b), but scorpion envenomation is not reported in Australian sheep.

5.9 Pregnancy toxaemia

Pregnancy toxaemia is a metabolic disease that may occur during late pregnancy. It is most likely to develop in fat or lean ewes when high energy requirements are not being met or, when feed intake is depressed (Pethick et al., 2005; Mavrogianni and Brozos, 2008). The resulting high blood ketone levels and low blood glucose results in high ewe mortality and, even if the ewe survives, increased lamb mortality (Henze et al., 1998). Barbagianni et al. (2015) observed a higher incidence of dystocia in ewes with pregnancy toxaemia and suggested this may be caused by impaired hormonal mechanisms due to poor ewe nutrition or reduced gestation length. Ewes that recover may develop dystocia or have a slow birth process resulting in metritis and stillborn lambs (Andrews, 1997). There are also reports that hypocalcaemia reduces abomasal and rumen motility and may precipitate pregnancy toxaemia in ewes (Friend et al., 2020). A combination of pregnancy toxaemia and hypocalcaemia would likely cause uterine inertia. Pregnancy toxaemia has been reported to have relatively low incidence of 0.5 – 2% of the flock (Andrews, 1997; Lane et al., 2015) and is therefore unlikely to be a major contributor to dystocia in ewes.

6 Dystocia impacts for the Australian sheep industry

6.1 Lamb deaths attributable to dystocia – systematic review

A literature search (methodology shown in Appendix 2) identified 880 papers including 209 duplicates. After initial screening of title and abstracts, 228 papers remained and were subject to full text screening and 10 papers were identified that fit inclusion criteria for the systematic review (Table 3).

6.1.1 Contribution of dystocia to lamb mortality.

The overall proportion of lamb mortality attributable to dystocia (pooled proportional mortality ratio) was 46% (Figure 2). The proportion of lamb mortality attributable to dystocia for the six Australian studies was 54.0% (95% confidence interval (CI): 46.7%; 61.2%), with the three most recent Australian studies ranging from 46 to 47%.

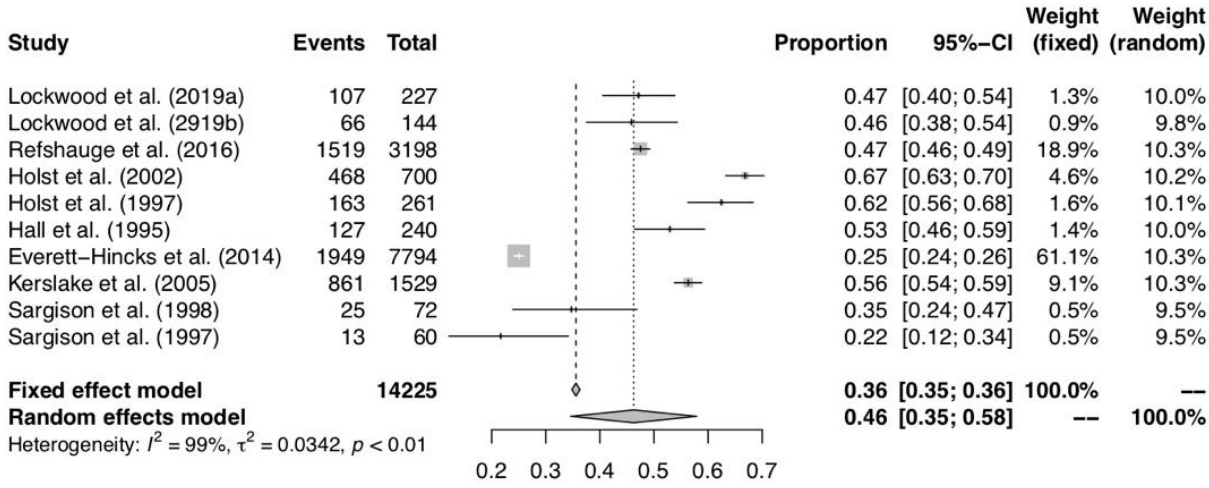

Figure 2. Forest plot of proportional mortality ratio for dystocia in lambs in Australia and New Zealand with 95% confidence interval shown in square parentheses.

Australian studies pre-dating 1990 that included post mortem examination of lambs, reported the proportion of lamb mortality attributable to dystocia ranging from 5% to 54% (Table 4). These studies did not include the birth injury (Dystocia C) category and central nervous system lesions were not part of inclusion criteria for cases categorized as stillbirth (Dystocia B). Therefore, these older studies are likely to underestimate the proportional mortality ratio for dystocia based on current definitions (Table 2).

The proportion of lamb mortality attributable to dystocia for the four New Zealand studies was 34.7% (95%CI: 19.0; 50.5%). None of these studies used methodology that included the birth injury (Dystocia C) category or presence of central nervous system lesions for categorising cases to stillbirth (Dystocia B) which could explain the apparent lower proportional mortality ratio compared to Australian studies (see section 2.2.2). Additionally, it is possible that climatic conditions in New Zealand lead to a higher absolute number of SME deaths, and as a consequence the relative contribution of dystocia is decreased. It is therefore not possible to conclude whether the proportion of lamb mortality attributable to dystocia is different between Australia and New Zealand.

Table 3. Summary of postmortem examination (PME) studies included in the systemic review for proportional mortality ratio in lambs attributable to dystocia

								Dystocia (n)		
Reference	**Year**	**Dam breed**	**Sire breed**	**Location**[a]	**Cause of death classification**	**Age** (days)	**PME** (n)	**Total**	**A (dystocia)**	**B (stillbirth)**	**C (birth injury)**
Lockwood et al. (2019b)	2016	Merino	Merino	WA	Holst (2004)	N/A	144	66	4	32	30
Lockwood et al. (2019a)	2017	Merino	Merino	WA	Holst (2004)	N/A	227	107	15	39	53
Refshauge et al. (2016)	2008-2011	Merino & Merino-cross	Mixed	Various [b]	Refshauge et al. (2016)	0 to 5	3198	1519	282	660	577
Holst et al. (2002)	1994-1996	Merino & Merino-cross	Mixed	NSW	(McFarlane, 1965; Haughey, 1973a; Duff et al., 1982)	0 to 3	700	468	138	55	275
Holst et al. (1997)	1994-1995	Merino & Merino-cross	Mixed	NSW	(McFarlane, 1965; Haughey, 1973a; Duff et al., 1982)	0 to 3	261	163	55	18	90
Hall et al. (1995)	1979-1981	Non-Merino	Merino	NSW	Not described	0 to 3	240	127	-	-	-
Everett-Hincks et al. (2014)	2007-2011	Non-Merino	-	NZ	Everett-Hincks and Dodds (2008)	0 to 3	7794	1949	-	-	-
Kerslake et al. (2005)	2003	Non-Merino	-	NZ	McFarlane (1965)	0 to 3	1529	861	728[c]	133[#]	-
Sargison et al. (1998)	1997	Non-Merino	-	NZ	McFarlane (1965)	N/A	72	25	-	-	-
Sargison et al. (1997)	1996	Non-Merino	-	NZ	McFarlane (1965)	N/A	60	13	-	-	-

[a]WA - Western Australia, NSW - New South Wales, NZ – New Zealand

[b] Study conducted at 9 Australian Sheep Cooperative Research Centre Information Nucleus Flock sites located across WA, South Australia (SA), Victoria (VIC) and NSW

[c] Kerslake et al. (2005) used 2 dystocia categories: primary dystocia (localised moderate/severe (> 3 mm) subcutaneous oedema on head, neck, brisket or rib cage), secondary dystocia (localised minor; visible, but not measurable) subcutaneous oedema on head, neck, brisket or rib cage)

N/A not available

Table 4. Summary of Australian postmortem examination (PME) studies with lamb autopsy pre-dating 1990 (not included in the systemic review)

			Cause of death category (% cases)				
Study	**State**[a]	**PME** (n)	**Dystocia**[b]	**Stillbirth**[b]	**Starvation-mismothering**[b]	**Exposure**	**Predation**
Moulk (1954)	QLD	453	5	-	30	11	34
McHugh and Edwards (1958)	VIC	512	17	19	31	1	11
Smith (1962)	QLD	27	26	11	48	-	-
Smith (1962)	QLD	34	3	-	82	-	-
Smith (1964)	QLD	981	12	1	67	-	15
Hughes et al. (1964)	NSW	8016	54	-	7	9	7
McDonald (1966)	VIC	390	19	3	32	5	33
Moore et al. (1966)	SA	157	9	3	35	-	12
Dennis (1974)	WA	4417	19	-	46	2	3
Luff (1980)	NSW	2534	18	-	58	-	8
Alexander et al. (1980)	NSW	634	-	-	-	9	-
Haughey (1983)	NSW	173	32	2	24	-	1
Jordan and Le Feuvre (1989)	QLD	115	17	4	67	9	9
Jordan and Le Feuvre (1989)	QLD	56	20	-	54	-	25
Jordan and Le Feuvre (1989)	QLD	58	10	-	69	-	-

[a] QLD – Queensland, VIC – Victoria, NSW - New South Wales, WA - Western Australia.

[b] note methodology used for these studies did not include birth injury (Dystocia C) category and presence of central nervous system lesions was not criteria for categorising cases to stillbirth (Dystocia B)

6.1.2 Contribution of dystocia to lamb mortality in Merino and non-Merino ewes

Proportional mortality attributed to dystocia was not different between Merino ewes (49%) and non-Merino ewes including cross breed with Merino dam or sire (46%; Figure 3).

Notably, wide variation was observed for non-Merino ewes across the different studies, with high heterogeneity (I^2 = 98.7%) indicating almost all of the observed variation is due to real differences in the population rather than sampling error. This was likely attributable to different breeds (and genotypes within breeds), sire types, number of ewes in different studies and methodology used to classify cases for dystocia. Australian studies contain relatively few cases for non-Merino ewes, and it is likely more data will be required to determine ewe breed effects independent of other factors such as sire breed and litter size.

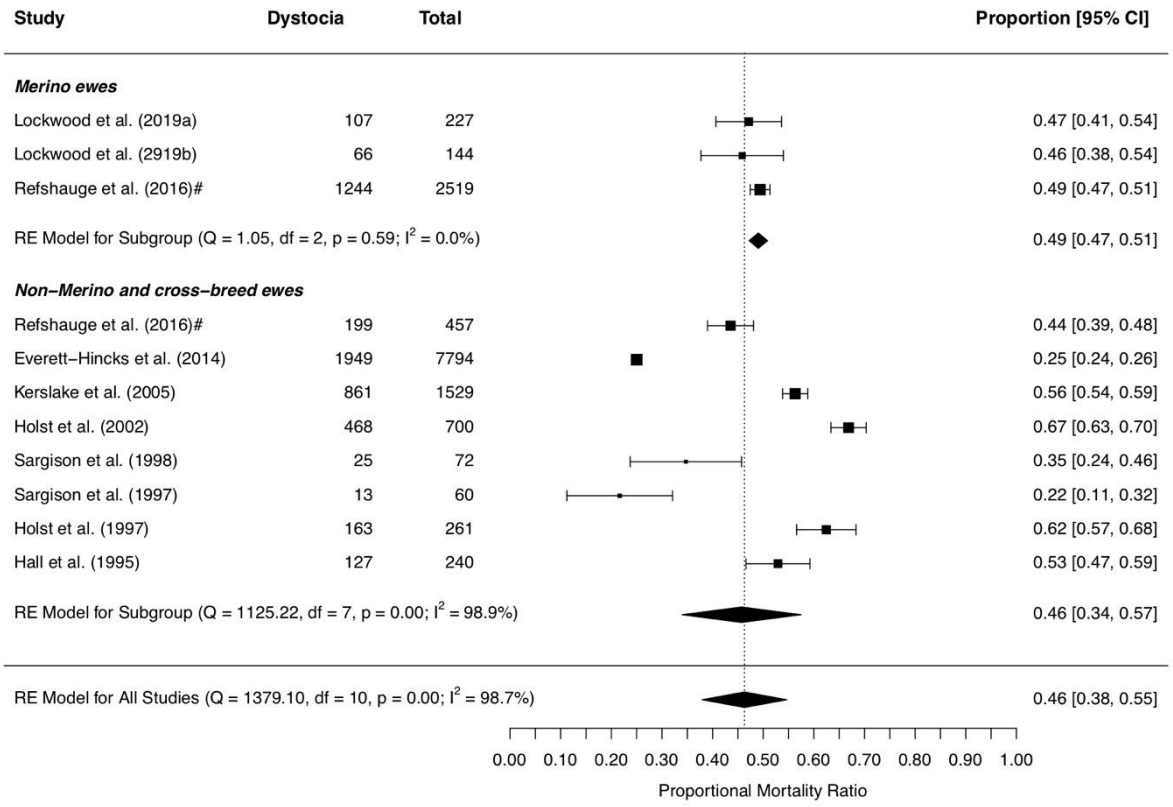

Figure 3. Forest plot of proportional mortality ratio of dystocia in Merino and non-Merino or cross breed ewes (with Merino dam or sire) with 95% confidence interval shown in square parentheses. #Data from Refshauge et al. (2016) was adapted to disaggregate Merino ewes from Merino-cross ewes as presented in Table 6.

6.1.3 Contribution of dystocia to lamb mortality in single and twin pregnancies.

Proportional mortality attributed to dystocia is higher for singles (70%) than twins (54%) or triplets (59%; Figure 4). However, dystocia is an important contributor to mortality of lambs for all litter sizes. Proportional mortality is affected by the absolute numbers of other causes of mortality, and reduced proportional mortality in twins may simply be due to a larger proportion dying of SME. Calculating the proportion of lambs born that died due to dystocia would account for the influence of other factors such as SME, however these data were not available. There is high heterogeneity between studies in each birth type category (I^2 > 80%), which suggests the true proportional mortality ratio is different between studies by birth type, and highlights the need for differences in environmental conditions to be included in analyses.

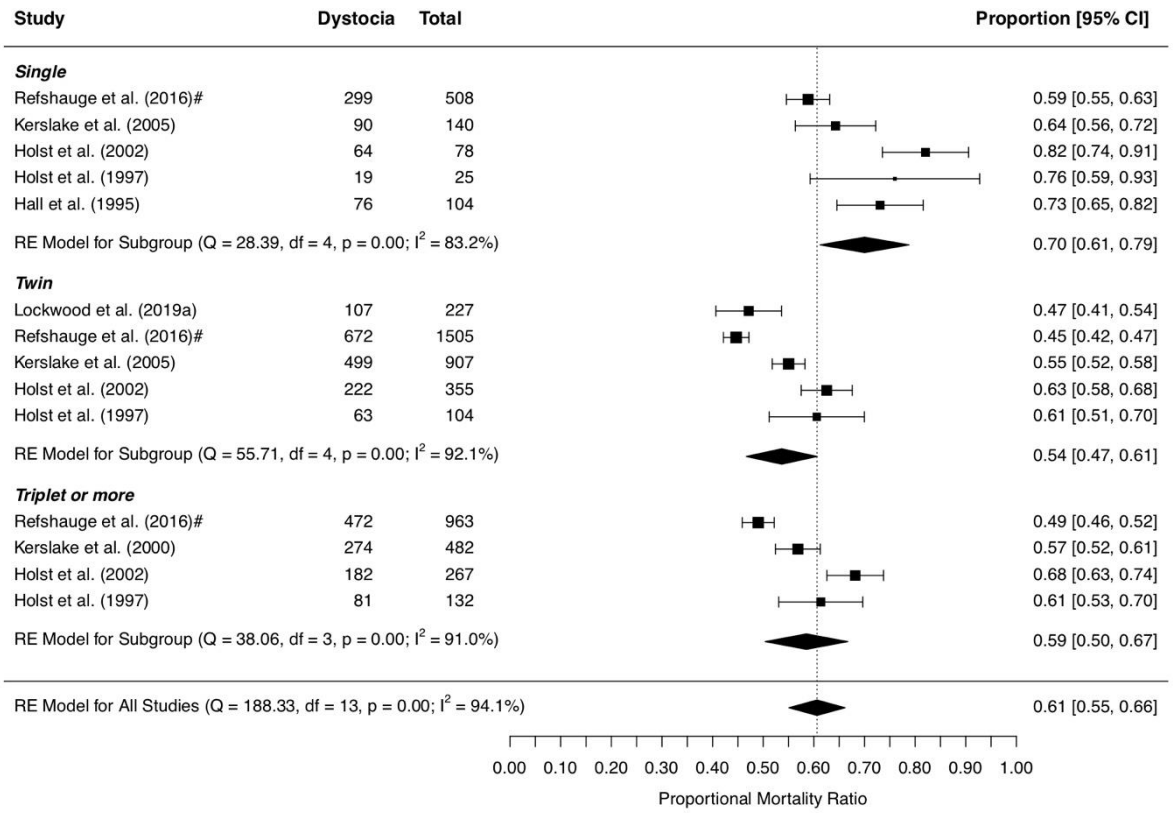

Figure 4. Forest plot of proportional mortality ratio of dystocia for lambs born to different birth types with 95% confidence interval shown in square parentheses. #Data from Refshauge et al., (2016) was adapted to disaggregate Merino ewes from Merino-cross ewes as presented in Table 6.

6.1.4 Lamb mortality attributable to dystocia in maiden and adult ewes.

Insufficient data were available to conduct pooled analyses comparing mortality for lambs born to maiden and adult ewes based on data available in the publications included in the systematic review.

6.2 Australian lamb and ewe mortalities attributable to dystocia

6.2.1 Lamb mortalities

Trompf et al. (2018) estimated national lamb mortality (Table 5) based on national flock of 42 million breeding ewes and industry average scanning and marking rates (Merino ewes scanning 125% and marking 86% lambs per 100 ewes joined, and non-Merino ewes scanning 155% and marking 112% lambs per 100 ewes joined).

Table 5. Estimated total lamb loss (million head/year) by ewe type and birth type (Trompf et al., 2018)

	Singles	**Twins**	**Triplets**	**Total**
Merino	2.8	6.8	0.3	9.9
Non-Merino	0.7	3.9	0.2	4.7
Total	**3.5**	**10.7**	**0.4**	**14.65**

Applying the proportion of wastage attributable to dystocia observed for Australian Sheep Cooperative Research Centre Information Nucleus Flock (Table 6) to lamb mortality for corresponding ewe breed and litter size categories (Table 5) indicates that 6.9 million lambs per year die from dystocia in Australia (Table 7). Although proportional mortality for dystocia is higher for single lambs than twin or triplet lambs, total mortality for twins is higher and the number of twin lambs that die from dystocia is more than double that for singles.

Table 6. Proportional mortality for dystocia (%) including stillbirth and birth injury for post mortem examination (PME) of lambs with known pedigree and litter size from Australian Sheep Cooperative Research Centre Information Nucleus Flock (2008-2011). Data adapted from (Refshauge et al., 2016)

	Dystocia (% PME cases)		
Ewe type	**Single**	**Twin**	**Higher order multiples***
Merino (n=2519)	58	46	50
Non-Merino (n=457)	64	37	45

* includes quads and quins

Table 7. Estimated annual Australian total lamb dystocia mortalities (millions) (calculated from Table 5 and Table 6)

Ewe type	**Single**	**Twin**	**Triplets**	**Total**
Merino	1.6	3.1	0.1	4.9
Non-Merino	0.4	1.4	0.1	1.9
Totals	2.1	4.6	0.2	6.9

6.2.2 Mortalities and interventions in ewes

Dystocia requiring some form of intervention (easy or hard pull, malpresentation or veterinary assistance) was reported in 1,789 (7.3%) of 24,652 ewes in the Australian Sheep Cooperative Research Centre Information Nucleus Flock for which birth was observed (Horton et al., 2018). This was higher than 1.3% dystocia incidence reported by in a survey of 71 Australian farmers for ewes grazing wheat crops during late pregnancy and lambing, though for a subset of 24 farms with abnormally high ewe losses farmers reported dystocia for 4.6% ewes (McGrath et al., 2013a). Perinatal ewe mortality attributable to dystocia was not reported for these studies. The intensity of lambing rounds at the Australian Sheep Cooperative Research Centre Information Nucleus Flock study sites could have influenced the reported incidence as frequent inspection over lambing could have increased detection of dystocia and level of intervention compared to that expected for commercial extensive sheep production systems.

Ewe mortality attributable to dystocia is poorly described in the literature. Preliminary findings for Meat and Livestock Australia project L.LSM.0019 (Unlocking the Keys to Ewe Survival) indicate mean non-Merino ewe mortality of 2.5% in the perinatal period on 30 commercial farms located predominantly in Victoria and Western Australia. Dystocia was reported as a suspected cause of death by participating farmers in 34% of cases, and this was consistent with veterinary post-mortem examinations in a subset of ewes identifying dystocia as the primary cause of death in 35% of cases (McQuillan et al., 2019). The preliminary findings for this study are consistent with observations for the Victorian Sentinel Flock Project where 35% of ewe deaths in the periparturient period were attributable to dystocia in a study of 20 farms on Victoria 2009-2012 (Source Rob Suter, Agriculture Victoria, unpublished data).

Assuming 2.5% ewe mortality in the perinatal period with 35% cases attributable to dystocia can be applied across a national flock of 42 million breeding ewes, ewe mortality attributable to dystocia is estimated at 367,500 head per year.

6.3 Financial impact of dystocia for Australian sheep industry

6.3.1 Impact of lamb mortality attributable to dystocia on national farm profit

Analysis to determine the value of lamb mortality attributable to dystocia was conducted using the MIDAS model described in detail by Young et al. (2014) using sheep sale prices consistent with a lamb price of AU$6.50/kg (carcass weight), wool price (eastern market indicator) of AU$14.50/kg and grain price of AU$286/t.

Applying the proportion of wastage attributable to dystocia observed for Australian Sheep Cooperative Research Centre Information Nucleus Flock (Table 4) to lamb mortality for ewe breed and litter size categories (Table 3) indicates mortality attributable to dystocia costs the Australian sheep industry AU$616 million per annum (Table 5).

Table 8. Reduction in Australian farm profit (national) for lamb mortality attributable to dystocia (AU$ millions per annum)

Ewe type	Single	Twin	Triplets	Total
Merino	170	241	10	421
Non-Merino	45	143	7	195
Totals	**215**	**384**	**17**	**616**

The impact of lamb mortality on farm profit is sensitive to lamb meat price, with impact of dystocia-related lamb mortality on national farm profit increasing as lamb price increases (Table 9). Impact on farm profit was less sensitive to wool price, consistent with Young et al. (2014).

Table 9. Change in impact of dystocia lamb mortality on national farm profit (AU$ millions per annum) with variable lamb sale price ($AUS per kg carcass weight)

	Lamb sale price (AU$ per kg carcass weight)					
	5.00	**6.00**	**6.50**	**7.00**	**8.00**	**9.00**
National farm profit impact (AU$ millions)	448	560	616	672	784	896

6.3.2 Impact of ewe mortality attributable to dystocia on national farm profit

The absence of reliable data on ewe mortality rates hampers estimation of economic cost associated with ewe deaths attributable to dystocia. Using estimates of 2.5% ewe mortality in the perinatal period with 35% cases attributable to dystocia based on the preliminary data reported by McQuillan et al. (2019), the estimated impact on Australian farm profit is AU$56 million per annum using MIDAS model described above. This modelling included the values and costs of changes in wool production and feed intake associated with producing a lamb.

Modelling used to determine this value assumes lamb mortality associated with ewe deaths are accounted for with lamb mortality (Table 8). If lamb mortality associated with death of ewe are combined, the impact on the Australian sheep industry is AU$96 million per annum.

The assumptions used are based on limited data, and it is not clear if mortality reported for L.LSM.0019 and the Victorian Ewe Sentinel project are applicable across different seasonal conditions, production systems and ewe genotypes.

6.3.3 Impact of maternal dystocia on national farm profit

Australian studies used to base assumptions to estimate value of ewe and lamb mortality attributable to dystocia do not differentiate maternal and fetal dystocia. International studies have attributed 25-51% of dystocia cases to maternal dystocia (Cloete et al., 1998; Sirinivas and Sreenu, 2009; Ennen et al., 2013; Mostefai et al., 2019), and applying this range to estimated value of lamb and ewe mortality attributable to dystocia indicates the impact of maternal dystocia on Australian farm profit ranges from AU$168 – $342.7 million per annum (Table 10).

Table 10. Impact of dystocia on national farm profit ($AU) and mortality for ewe and lambs

	Impact
Lamb mortality attributable to dystocia (national farm profit)	$616 million
Ewe mortality attributable to dystocia (national farm profit)	$56 million
Overall dystocia impact lamb + ewe mortality (national farm profit)	$672 million
Maternal dystocia (25-51% dystocia cases) impact on national farm profit	**$168-342.7 million**
Overall lamb mortality – dystocia	6.9 million lambs
Lamb mortality - maternal dystocia (25-51% dystocia cases)	**1.7 – 3.5 million lambs**
Overall ewe mortality – dystocia	367,500 ewes
Lamb mortality - maternal dystocia (25-51% dystocia cases)	**91,875 – 187,425 ewes**

The combined impact dystocia on farm profit due to lamb and ewe mortality is AU$672 million per annum (Table 10), or approximately $16.00 per ewe joined. This is considerably higher than AU$149 million per annum estimated by Lane et al. (2015) for a review of costs associated with endemic sheep and cattle diseases in Australia. Lane et al. (2015) used assumptions of lamb mortality associated with dystocia ranging 5.0-8.4% and ewe mortality 0.26-0.49% with flock structure based

on 2010-2011 data (73 million sheep, 42 million breeding ewes). Assumptions for meat and wool prices used in modelling were not reported.

6.3.4 Impacts not captured in financial cost estimates

The modelling used to assess impacts on national farm profit has not included impact of any long term reduction in productivity for affected ewes and lambs that survive, nor expenditure on prevention and treatment, such as labour costs for increased supervision of lambing ewes, nutrition management of pregnant ewes, or selection/genetic strategies aimed at mitigating risk.

The estimation of costs reported describe impact on Australian farm profit, and not impacts for the full sheep meat supply chain (e.g. processors, retailers etc). Lamb and ewe mortality has post-farmgate implications for sheep meat supply chain, especially where this impacts sustainability of national ewe population and lamb supply.

The effect of dystocia on animal welfare and associated social licence for the sheep meat industry is more difficult to quantify, requiring willingness to pay studies.

7 Mitigation strategies and gaps in understanding

This review has focussed on understanding of aetiology of dystocia of maternal origin, identified nutritional and non-nutritional pathways that affect parturition and dystocia in ewes, and estimated impacts of dystocia on national farm profit and ewe and lamb mortality in Australia.

A number prospective mitigation strategies have been identified that have varying degree of evidence to support a role in reducing dystocia impacts (Table 11). A number of these recommendations are hypothesised to reduce impact through improving survival of lambs born with birth injury subsequent to difficult birth by extrapolating findings from studies exploring strategies for improving lamb survival more generally. There are major gaps in understanding about the relationship between hypoxic injury and lamb viability, and what level of intervention is required to have meaningful impact on survival of lambs with birth injury (Dystocia C), and it remains unclear to what extent generic lamb survival strategies impact survival of lambs born with birth injury.

Table 11. Mitigation options for maternal dystocia and impact on ewe and lamb mortality**.** *Italicised text indicates statement based on limited information or extrapolation in relation to dystocia (more research may be required)*

Tactics	Tools	Goal	Knowledge gaps for tactical management
Differential management of single- and multiple-bearing ewes	• *CS monitoring* • Avoid over-fat ewes • Avoid thin ewes	• Reduce dystocia for large single and small multiple lambs • Reduce dystocia secondary to metabolic disease	• Optimum condition score profile • Variation in birthweight of lambs from ewes with a similar CS • Influence of ewe nutrition (including glycogen stores) on parturition, length of pregnancy and the HPA axis
Ram selection	• Birthweight ASBV • Lamb Ease ASBV • *Breed/size*	• Reduce foetopelvic disproportion	• Current knowledge on impact of breed is inconclusive • Low heritability of dystocia related traits • Limited knowledge on genetic correlations between production and indicator traits
Do not mate small, immature ewes	• Liveweight monitoring	• Reduce foetopelvic disproportion	• Optimum proportion of mature weight at joining
Address mineral nutrition during late pregnancy and lambing	• *Consider access to mineral and vitamin supplements.*	• Reduce dystocia secondary to metabolic disease	• Benefits of minerals and vitamins. • Role of subclinical hypocalcaemia on uterine function.
Reduce mob size	• Reduce disturbance during parturition •	• Reduce dystocia through interrupted parturition • Reduce desertion of compromised lambs	• Optimum mob and paddock size for lambing
Provide edible shelter during lambing	• Manage exposure risk • Provide feed near the birth site	• Reduce desertion of compromised lambs (birth injury) by providing feed and shelter near the birth site • Improve survival of compromised lambs (birth injury) by reducing exposure (wind chill)	• Benefit of edible shelter for lamb and ewe survival

Table 11 (continued). Mitigation options for maternal dystocia and impact on ewe and lamb mortality. *Italicised text indicates statement based on limited information or extrapolation in relation to dystocia (more research may be require*

Tactics	Tools	Goal	Knowledge gaps for tactical management
Provide appropriate supervision during lambing	• Avoid stressing ewes over lambing and minimise disturbance • Appropriate obstetric intervention for ewes	• Reduce dystocia through interrupted parturition (avoid over-disturbance) • Improve survival of compromised lambs (birth injury) by supporting ewe-lamb bond (not disturbing ewe during critical bonding period) • Reduce ewe mortality through appropriate obstetric intervention (reduce infection, trauma)	• Influence of ewe stress on HPA axis and impact on parturition • Level of monitoring and intervention to balance ewe and lamb mortality in extensive systems
Manage exposure to oestrogenic pastures	• Graze pregnant ewes on non-oestrogenic pasture. • Assess pasture composition and manage pasture species	• Reduce dystocia due to uterine inertia or failure of cervical dilation	• Understanding of extent and potency of oestrogenic pastures across different regions. • Role of clover and non-clover legumes on dystocia
Avoid other toxins and endocrine disrupting compounds	• Pasture monitoring • Fertiliser management • Herbicide, fungicide and pesticide management	• Reduce dystocia due to uterine inertia or congenital abnormalities	• Relative impact of teratogenic plant ingestion on occurrence of dystocia • Relative impact of endocrine disrupting chemicals on occurrence of dystocia
Predator control	• Dog, fox and pig control	• Reduce dystocia through interrupted parturition • Improve survival of compromised lambs (birth injury) by supporting ewe-lamb bond (not disturbing ewe during critical bonding period)	• Influence of ewe stress on HPA axis and impact on parturition
Time of lambing	• Avoid lambing in extreme climatic conditions • *Reduce disturbance from supplementary feeding* • *Adequate feed at or near the birthsite*	• Reduce dystocia through interrupted parturition • Improve survival of compromised lambs • Reduce desertion of compromised lambs (birth injury) by providing feed and shelter near the birth site	• Relative impact of environmental stress on dystocia • Impact of time of lambing on dystocia • Seasonal variation in ringwomb incidence
Ewe selection and culling	• Selection of maternal sire using traits that improve Lamb Ease in daughters • Sire breed • Size (liveweight) • Cull ewes with history of dystocia		• Repeatability for dystocia • BCA for culling affected ewes • Assessment of pelvic conformation and impact on dystocia

In addition to knowledge gaps for tactical management (Table 11), a number of additional strategic research gaps relating to fundamental processes involved in dystocia have been identified (Table 12).

Table 12. Additional strategic research gaps for fundamental processes involved with dystocia

Strategic research gaps	Relative role of ring womb and seasonal variation in incidence
	Link between over-conditioning in ewes and dystocia – physical or hormonal impacts on parturition and lamb viability
	Role of gestation length on dystocia risk
	Role of hormonal changes on dystocia risk
	Role of sub-clinical hypocalcaemia on uterine function
	Role of stress-nutrition interactions in HPA axis function and impact on parturition

8 Prioritisation of identified gaps and proposed R&D programs

Three key control points have been identified as priorities for research, management and reduction of dystocia (Table 13). These are; 1. The preparation of the ewe and developing fetus for birth and survival ('Fitness to Lamb'); 2. The stressors that directly influence the process of parturition and ability to recover from a difficult birth ('Ready to Rear') and; 3. The within and between breed genetics that contribute to dystocia risk ('Bred to Deliver').

A staged approach is recommended to address the knowledge gaps and develop verified recommendations. This would begin with an investigation and potential re-analysis of currently available datasets together with a national survey of producers. A second stage of controlled field experiments, producer demonstration with aligned basic research is suggested that reflects results from the initial step. Aligned basic research will characaterise mechanisms that lead to improved lamb and ewe survival. This information will then support extension of recommendations across environments, genotypes and management systems.

1. Fitness to Lamb

Factors including lamb birthweight, and ewe maturity, liveweight, condition score profile, fatness, glycogen concentration in uterine muscle and mineral status all influence the fitness of the ewe to give birth and lamb viability. There is currently insufficient information to provide tested recommendations to ensure fitness to lamb. The following research approach is recommended:

a. Investigation and possible re-analysis of existing datasets where fitness to lamb control points and dystocia have been measured or may be indicated.
b. Survey producers (particularly those with a history of dystocia) and collate information on measured risk factors and seasonal variation.
c. Field studies integrated with producer demonstration sites incorporating range of age groups, genotypes, years (seasonal variation) and environments to test and define ewe and lamb condition, fatness and metabolic state required to minimise the risk of dystocia. Where possible consider add-on to existing research.
d. Complementary basic research that overlays field studies to determine underlying mechanisms associated with dystocia with focus on metabolic and hormonal changes that impact birth. To include studies/measurements on glycogen in uterine muscle and ewe aerobic fitness, sub-clinical hypocalcaemia, pregnancy toxaemia and oxidative stress. Consider support for PhD students.

Progress to c. and d. dependant on results from a. and b. Concurrent completion of d. with c. is likely to provide information that will support the extrapolation of results that will reduce the requirements for testing years, environments and genotypes.

Defining Fitness to Lamb was considered the highest priority for future research.

2. Ready to Rear

The short-term process of parturition and immediate recovery after a difficult birth are closely related to stress and environment influences. The stress and reproductive hormones play a major role in the initiation and control of parturition and thermoregulation in the sheep. These hormones are under both endogenous control and exogenous influence. As with the 'Fitness to Lamb' theme, there are knowledge gaps that limit the certainty of general recommendations. The following research approach is recommended:

a. Investigation and possible re-analysis of existing datasets where flock (mob) size, shelter availability and disturbance have been measured and possibly associated with dystocia.

b. Survey producers (particularly those with a history of dystocia) and collate information on stress and environmental conditions around parturition and time of lambing.
c. Field and producer demonstration studies to investigate the impacts of flock (mob) size, supervision, shelter availability and weather conditions on the incidence of risk dystocia. Where possible consider add on to existing research.
d. Complementary overlay to field studies to include basic research to investigate the relationship between hypoxia, hormonal change and thermoregulation in the lamb and the interactions between stress hormone changes and the parturition process. Consider support for PhD students.
e. Continued studies into the prevalence and consequences of oestrogenic pastures, with a particular focus on identification, measurement and eventually eradication of oestrogenic species impacting livestock production.

3. Bred to Deliver

There is a genetic component to dystocia. This is at least partly explained by incompatibility in physical size and dimensions of the ram, ewe and lamb. The repeatability for individual ewes is uncertain. There is also a heritable component although heritability of dystocia and indicator traits appears to be low. Positive correlations with some favourable production traits requires clarification. The following research approach is recommended:

a. Continued collection of data to assess genetic correlations between dystocia and production traits. Use within breeding indices where required. It is assumed this will be done as part of normal business by SGA.
b. Include breed, genotype comparisons for risk of dystocia in as part of field studies.
c. Investigate available data sets for evidence of repeatability.

Table 13: Programs of work to address prioritised R&D gap for three key control points

	Broad R&D focus	Gaps addressed by program	Notes	Broad R&D approach across program
Fit to Lamb	Ewe maturity, weight, condition score and nutritional status	Target condition score profile for specific genotypes and litter size.	• Highest ranking by review team • Important to establish value of condition profile (versus one-off condition score measurement) and relationship with lamb mortality • Fieldwork linked to basic science required to address existing gaps	• Re-analysis of existing datasets. • Survey producers to collate information on risk factors, seasonal variation and potential barriers to adoption • Field and producer demonstration studies to test and define targets for weight and condition score profile and metabolic state • Basic research support overlayed on field and demonstration sites to define mechanistic changes associated with dystocia. To include nutritional, metabolic and hormonal profiling. Align with support for PhD and post-doctoral studies on fatness, hypocalcaemia and oxidative stress.
		Target weight at joining and lambing for maidens to optimise lamb survival	• Larger R&D gap for maiden hoggets (joined approximalely 18 months) than ewe lambs (joined 7-10 months) • Significant gaps preclude evidence-based recommendations for different age groups - maidens (ewe lambs and/or hoggets) versus adults	
		Influence of ewe nutrition (including glycogen stores, sub-clinical pregnancy toxaemia and oxidative stress) on parturition, gestation length and HPA axis, and impact on parturition and lamb viability	• Research to underpin management/adoption recommendations • Nutrition studies should include breed/genotype overlay ('breed effect') • Some crossover with research in 'Ready to Rear' (e.g. stress-nutrition interactions impacting HPA axis and parturition)	
		Establish incidence of sub-clinical hypocalcaemia across different production systems Establish links between sub-clinical hypocalcaemia, pregnancy toxaemia and dystocia, including measures of lamb and ewe mortality	• Research required to establish association with dystocia and underpin recommendations for mitigation given variability observed across regions and seasons	
	Lamb birthweight	Establish variation in birthweight of lambs from ewes with a similar condition score profile (within genotype) and association with dystocia	• Initial desktop review of existing datasets in Australia and NZ for preliminary analysis and define what additional work is needed. • Add relevant measurements onto existing projects (ewe condition score, lamb birthweights)	

Table 13 (continued): Programs of work to address prioritised R&D gap for three key control points

	Broad R&D focus	Gaps addressed by program	Notes	Broad R&D approach across program
Ready to Rear	Lambing paddock and flock characteristics	Optimum flock (mob) and paddock size	• 'Add-on' relevant measures to existing/proposed R&D to establish link with dystocia (e.g. addition of lamb and ewe autopsies)	• Re-analysis of existing datasets • Survey producers to collate information on risk factors • Field and producer demonstration studies to investigate the impacts of flock size, supervision, shelter and weather conditions on the incidence of dystocia • Basic research support overlayed on field and demonstration sites to define the relationship between hypoxia, hormonal change and thermoregulation in the lamb and the interactions between stress hormone changes and the parturition process. Align with support for PhD and post doctoral studies • Continued studies into the prevalence and consequences of oestrogenic pastures, with a particular focus on identification, measurement and eventually eradication
		Impact of edible shelter on dystocia and survival of compromised lambs (ewe and lamb mortality)		
		'Best practice' supervision and level of disturbance for extensive production systems	• Sensor technology to drive R&D capacity to measure impact of disturbance on ewe behaviour and outcomes for ewe and lamb survival. Sensor technology also has implications for adoption (e.g. remote monitoring) • Establishing risks and benefits for different levels of monitoring (disturbance) will inform BCA for different management practices	
	Seasonal variation	Seasonal variation in dystocia (including ringwomb)		
		Impact of time of lambing on risk of dystocia	• Understanding impact of time of lambing on risk of dystocia will inform targeted extension/adoption messages appropriate to farming system and time of lambing	
	Stressors that impact parturition and lamb viability	Role of environmental and managements stress on risk of dystocia, including role of hormonal and metabolic changes	• Research to establish mechanisms that impact parturition and lamb viability and will underpin management/adoption recommendations across environments and management systems • Some crossover with research on 'Fitness to Lamb' • Studies should include breed/genotype overlay ('breed effect')	
		Factors impacting neonatal lamb thermoregulation	• Research to establish association between hypoxic injury and capacity for thermoregulation in neonatal period • Genetic (breed) component should be included • Potential to impact lamb mortality associated with starvation-mismothering-exposure as well as dystocia	
		Impact of oestrogenic forages (clover and non-clover legumes), plant teratogens and other endocrine-disrupting compounds on lamb and ewe survival	• 'Add-on' to existing/proposed R&D on oestrogenic clover to establish link with dystocia (e.g. lamb and ewe autopsy)	

Table 13 (continued): Programs of work to address prioritised R&D gap for three key control points

	Broad R&D focus	Gaps addressed by program	Notes	Broad R&D approach across program
Bred to Deliver	Heritability Indicator traits Repeatability	Genetic correlations of production and indicator traits Repeatability for dystocia in context of other risk factors (ewe age, condition score profile, sire, etc). Ram size and dimensions	• Addition of lamb and ewe autopsy to larger studies could be a cost effective strategy for answering questions. • No easy solutions indicated in the review – heritability low and repeatability not well defined • Selection for lamb survival traits is complex in context of broader production indexes • Possibly already covered by Sheep Genetics - selection strategies for reducing lamb deaths associated with dystocia (including Dystocia B and C) • Understanding repeatability important to establish BCA for culling ewes that require intervention and/or fail to raise lambs (lamb mortality due to dystocia) • Establish role of qualitative genetics vs 'genomics'	• Support Sheep Genetics Australia in establishing genetic correlations between dystocia and production traits • Consult with Sheep Genetics Australoia to ensure that appropriate breed and genotype overlay is incorporated into field studies and basic research that establish dystocia risk factors and nutrition/management targets (identify genotype x management/nutrition interactions) • Investigate available datasets for evidence of repeatability and establish need for new data to determine BCA for culling strategies.

9 Bibliography

Adams, N.R., 1995. Detection of the effects of phytoestrogens on sheep and cattle. Journal of Animal Science 73, 1509-1515.

Adams, N.R., Nairn, M.E., 1983. The nature of dystokia in ewes after grazing oestrogenic subterranean clover. Australia Veterinary Journal 60, 124-125.

Alexander, G., 1984. Constraints to lamb survival. In: Lindsay, D.R., Pearce, D.T. (Eds.), Reproduction in Sheep, Australian Academy of Science, in conjunction with the Australian Wool Corporation, Canberra, ACT, pp. 199-209.

Alexander, G., Lynch, J.J., Mottershead, B.E., Donnelly, J.B., 1980. Reduction in lamb mortality by means of grass wind-breaks: Results Of A Five-Year Study. Proceedings of the Australian Society of Animal Production, pp. 329-332.

Alexander, G., Williams, D., 1971. Heat stress and development of the conceptus in domestic sheep. The Journal of Agricultural Science 76, 53-72.

Ali, A.M.H., 2011. Causes and management of dystocia in small ruminants in Saudi Arabia. Journal of Agricultural and Veterinary Sciences 4, 95-108.

Anderson, A.B., Webb, R., Turnbull, A.C., 1981. Oestrogens and parturition. Journal of Endocrinology 89 Suppl, 103P-117P.

Andrews, A., 1997. Pregnanacy toxaemia in the ewe. In Practice 19, 306-312.

Arnett, D.W., Holland, G.L., Totusek, R., 1971. Some effects of obesity in beef females. Journal of Animal Science 33, 1129-1136.

Arnold, G.W., Morgan, P.D., 1975. Behaviour of the ewe and lamb at lambing and its relationship to lamb mortality. Applied Animal Ethology 2, 25-46.

Arthur, G.H., 1975. Veterinary Reproduction and Obstetrics, Baillière Tindall, London.

Atkins, K.D., 1980. Selection for skins folds and fertility. Proceedings of the Australian Society of Animal Production 13, 174-176.

Balduzzi, S., Rücker, G., Schwarzer, G., 2019. How to perform a meta-analysis with R: a practical tutorial. Evidence Based Mental Health 22, 153-160.

Banchero, G.E., Quintans, G., Martin, G.B., Lindsay, D.R., Milton, J.T.B., 2004. Nutrition and colostrum production in sheep. 1. Metabolic and hormonal responses to a high-energy supplement in the final stages of pregnancy. Reproduction, Fertility and Development 16, 633-643.

Barbagianni, M.S., Spanos, S.A., Ioannidi, K.S., Vasileiou, N.G.C., Katsafadou, A.I., Valasi, I., Gouletsou, P.G., Fthenakis, G.C., 2015. Increased incidence of peri-parturient problems in ewes with pregnancy toxaemia. Small Ruminant Research 132, 111-114.

Barlow, R.M., Gardiner, A.C., Angus, K.W., Gilmour, J.S., Mellor, D.J., Cuthbertson, J.C., Newlands, G., Thompson, R., 1987. Clinical, biochemical and pathological study of perinatal lambs in a commercial flock. Veterinary Record 120, 357.

Barowicz, T., 1979. Inhibitory effect of adrenaline on oxytocin release in the ewe during the milk-ejection reflex. Journal of Dairy Research 46, 41-46.

Basarab, J.A., Rutter, L.M., Day, P.A., 1993. The efficacy of predicting dystocia in yearling beef heifers: I. Using ratios of pelvic area to birth weight or pelvic area to heifer weight. Journal of Animal Science 71, 1359-1371.

Basher, E.B., 2006. Clinical study on fetal congenital defects causing dystocia in Awassi ewes. Iraqi Journal of Veterinary Sciences 20, 181-189.

Behrendt, R., Hocking Edwards, J.E., Gordon, D., Hyder, M., Kelly, M., Cameron, F., Byron, J., Raeside, M., Kearney, G., Thompson, A.N., 2019. Offering maternal composite ewes higher levels of nutrition from mid-pregnancy to lambing results in predictable increases in birthweight, survival and weaning weight of their lambs. Animal Production Science 59, 1906-1922.

Bellows, R.A., Gibson, R.B., Anderson, D.C., Short, R.E., 1971. Precalving Body Size and Pelvic Area Relationships in Hereford Heifers. Journal of Animal Science 33, 455-457.

Ben Nasr, H., Hammami, S., Mion, G., Sahnoun, Z., Chouaiekh, F., Rebaï, T., Kassis, M., Goyffon, M., Zeghal, K., 2007a. Effects of Buthus occitanus tunetanus envenomation on an experimental murine model of gestation. Comptes Rendus Biologies 330, 890-896.

Ben Nasr, H., Hammami, T.S., Sahnoun, Z., Rebai, T., Bouaziz, M., Kassis, M., Zeghal, K.M., 2007b. Scorpion envenomation symptoms in pregnant women. Journal of Venomous Animals and Toxins including Tropical Diseases 13, 94-102.

Bennetts, H.W., Underwood, E.J., Shier, F.L., 1946. A specific breeding problem of sheep on subterranean clover pastures in Western Australia. Australian Veterinary Journal 22, 2-12.

Benyshek, L.L., Little, D.E., 1982. Estimates of genetic and phenotypic parameters associated with pelvic area in Simmental cattle. Journal of Animal Science 54, 258-263.

Bitman, J., Cecil, H.C., Wood, J.R., Wrenn, T.R., 1967. Comparison of oestrogen-induced glycogenesis in the uterus of the rat, rabbit and sheep. Acta Endocrinologica 54, 505 - 513.

Bontekoe, E.H., Blacquiere, J.F., Naaktgeboren, C., Dieleman, S.J., Willems, P.P., 1977. Influence of environmental disturbances on uterine motility during pregnancy and parturition in rabbit and sheep. Behaviour Processes 2, 41-73.

Braems, G.A., Matthews, S.G., Challis, J.R., 1996. Differential regulation of proopiomelanocortin messenger ribonucleic acid in the pars distalis and pars intermedia of the pituitary gland after prolonged hypoxemia in fetal sheep. Endocrinology 137, 2731 – 2738.

Braun, W., 2007. Parturition and dystocia in the goat. Current Therapy in Large Animal Theriogenology, Elsevier, pp. 555-558.

Brien, F.D., Cloete, S.W.P., Fogarty, N.M., Greeff, J.C., Hebart, M.L., Hiendleder, S., Edwards, J.E.H., Kelly, J.M., Kind, K.L., Kleemann, D.O., Plush, K.L., Miller, D.R., 2014. A review of the genetic and epigenetic factors affecting lamb survival. Animal Production Science 54, 667-693.

Brien, F.D., Hebart, M.L., Smith, D.H., Edwards, J.E.H., Greeff, J.C., Hart, K.W., Refshauge, G., Bird-Gardiner, T.L., Gaunt, G., Behrendt, R., Robertson, M.W., Hinch, G.N., Geenty, K.G., van der Werf, J.H.J., 2010. Opportunities for genetic improvement of lamb survival. Animal Production Science 50, 1017-1025.

Brockway, J., McDonald, J., Pular, J., 1963. The energy cost of reproduction in sheep. Journal of Physiology 167, 318-327.

Brounts, S.H., Hawkins, J.F., Baird, A.N., Glickman, L.T., 2004. Outcome and subsequent fertility of sheep and goats undergoing cesarean section because of dystocia: 110 cases (1981–2001). Journal of the American Veterinary Medical Association 224, 275-281.

Brown, D.E., Harrison, P.C., Hinds, F.C., Lewis, J.A., Wallace, M.H., 1977. Heat stress effects on fetal development during late gestation in the ewe. Journal of Animal Science 44, 442-446.

Brown, D.J., Jones, R.M., Hinch, G.N., 2014. Genetic parameters for lamb autopsy traits. Animal Production Science 54, 736.

Bruckmaier, R.M., Wellnitz, O., Blum, J.W., 1997. Inhibition of milk ejection in cows by oxytocin receptor blockade, α-adrenergic receptor stimulation and in unfamiliar surroundings. Journal of Dairy Research 64, 315-325.

Caple, I.W., Heath, J.A., Grant, I.M., 1988. Calcium requirements of sheep during pregnancy, lactation and growth. Proceedings of the Nutrition Society of Australia 13, 33-40.

Celi, P., 2010. The role of oxidative stress in small ruminants' health and production. Revista Brasileira de Zootecnia 39, 348-363.

Celi, P., Bush, R., 2010. Pregnancy, lambing and survival. In: Cottle, D.J. (Ed.), International Sheep and Wool Handbook, Nottingham University Press, Nottingham, UK, pp. 223-257.

Challis, J.R.G., 1995. CRH, a placental clock and preterm labour. Nature Medicine 1, 416 - 417.

Challis, J.R.G., 2013. Prostaglandins and parturition. 51. Kongreß der Deutschen Gesellschaft für Gynäkologie und Geburtshilfe: Gynäkologie und Gynäkologische Onkologie, Geburtshilfe,

Perinatologie und Pränatale Diagnostik, Gynäkologische Endokrinologie und Reproduktionsmedizin. Springer-Verlag, p. 109.

Challis, J.R.G., Brooks, A.N., 1989. Maturation and activation of hypothalamic-pituitary adrenal function in fetal sheep. Endocrine Reviews 10, 182-204.

Challis, J.R.G., Olsen, D.M., 1988. Parturition. In: Knobil, E., Neill, J.D. (Eds.), The Physiology of Reproduction, Raven Press, New York, USA, pp. 2177-2216.

Challis, J.R.G., Sloboda, D., Matthews, S.G., Holloway, A., Alfaidy, N., Patel, F.A., Whittle, W., Fraser, M., Moss, T.J., Newnham, J., 2001. The fetal placental hypothalamic-pituitary-adrenal (HPA) axis, parturition and post natal health. Molecular and Cellular Endocrinology 185, 135-144.

Chew, C.S., Rinard, G.A., 1979. Glycogen levels in the rat myometrium at the end of pregnancy and immediately postpartum. Biology of Reproduction 20, 1111-1114.

Clark, N.T., 1965. Effect of antepartum injections of stilboestrol dipropionate on lambing behaviour of ewes. Australian Veterinary Journal 41, 300-300.

Clegg, M.T., 1959. Factors affecting gestation length and parturition. Reproduction in Domestic Animals 1, 509.

Cloete, S.W., Misztal, I., Olivier, J.J., 2009. Genetic parameters and trends for lamb survival and birth weight in a Merino flock divergently selected for multiple rearing ability. Journal of Animal Science 87, 2196-2208.

Cloete, S.W.P., 1994. Rearing performance of Merino, SA Mutton Merino and Dormer ewes in relation to live mass, reproduction and pelvic dimensions. Journal of the South African Veterinary Association 65, 10-17.

Cloete, S.W.P., Scholtz, A.J., Ten Hoope, J.M., Lombard, P.J.A., Franken, M.C., 1998. Ease of birth relation to pelvic dimensions, litter weight and conformation of sheep. Small Ruminant Research 31, 51-60.

Coburn, K.M., Vevea, J.L., 2019. weightr: Estimating Weight-Function Models for Publication Bias. R package version 2.0.2.

Conington, J., Moore, K., Dwyer, C.M., 2014. Using genetic selection to improve lamb survival in extensive sheep production systems. Proceedings of the European Association of Animal Production, Copenhagen, 87.

Cook, B.R., Tess, M.W., Kress, D.D., 1993. Effects of selection strategies using heifer pelvic area and sire birth weight expected progeny differences on dystocia in first-calf heifers. Journal of Animal Science 71, 602-607.

Coppock, R.W., Dziwenka, M.M., 2017. Teratogenesis in livestock. In: Gupta, R.C. (Ed.), Reproductive and Developmental Toxicology, Academic Press, London, UK, pp. 1391-1408.

Coppock, R.W., Jacobsen, B.J., 2009. Mycotoxins in animal and human patients. Toxicology and Industrial Health 25, 637-655.

Crankshaw, D.J., Challis, J.R.G., Patrick, J.E., Daniel, E.E., 1979. Calcium regulation in the myometrium of pregnant sheep. Gynecological and Obstetric Investigations 10, 298-305.

Crisp, T.M., Clegg, E.D., Cooper, R.L., Wood, W.P., Anderson, D.G., Baetcke, K.P., Hoffmann, J.L., Morrow, M.S., Rodier, D.J., Schaeffer, J.E., Touart, L.W., Zeeman, M.G., Patel, Y.M., 1998. Environmental endocrine disruption: an effects assessment and analysis. Environmental Health Perspectives 106 11-56.

Croker, K., Curtis, K., Speijers, J., 2009. Times of lambing in Australian flocks - 2005 to 2007. Department of Agriculture and Food, Perth, p. 21.

Curtis, C., Erb, H., Sniffen, C., Smith, R., Powers, P., Smith, M., White, M., Hillman, R., Pearson, E., 1983. Association of parturient hypocalcemia with eight periparturient disorders in Holstein cows. Journal of the American Veterinary Medical Association 183, 559-561.

Dalton, D.C., Knight, T.W., Johnson, D.L., 2012. Lamb survival in sheep breeds on New Zealand hill country. New Zealand Journal of Agricultural Research 23, 167-173.

Darwish, R.A., Ashmawy, T.A.M., 2011. The impact of lambing stress on post-parturient behaviour of sheep with consequences on neonatal homeothermy and survival. Theriogenology 76, 999-1005.

Davies, H.L., Rossiter, R.C., Maller, R., 1970. The effects of different cultivars of subterranean clover (T. subterraneum L.) on sheep reproduction in the south-west of Western Australia. Australian Journal of Agricultural Research 21, 359-369.

Dawson, L.E.R., Carson, A.F., McClinton, L.O.W., 2002. Comparison of the productivity of Texel and Rouge de l'Ouest ewes and their crosses. Animal Science 75, 459-468.

De Weerth, C., Buitelaar, J.K., 2005. Physiological stress reactivity in human pregnancy—a review. Neuroscience and Biobehavioral Reviews 29, 295-312.

Dennis, S.M., 1974. Perinatal lamb mortality in Western Australia. 1. General procedures and results. Australian veterinary journal 50, 443-449.

Douglas, A.J., Brunton, P.J., Bosch, O.J., Russell, J.A., Neumann, I.D., 2003. Neuroendocrine responses to stress in mice: hyporesponsiveness in pregnancy and parturition. Endocrinology 144, 5268-5276.

Duff, X.J., McCutcheon, S.N., McDonald, M.F., 1982. Central nervous system injury as a determinant of lamb mortality. Proceedings of the New Zealand Society of Animal Production, pp. 15-17.

Dutra, F., Banchero, G., 2011. Polwarth and Texel ewe parturition duration and its association with lamb birth asphyxia. Journal of Animal Science, 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, C., Lawrence, A., Bishop, S., Lewis, M., 2003. Ewe-lamb bonding behaviours at birth are affected by maternal undernutrition in pregnancy. British Journal of Nutrition 89, 123 - 136.

Dwyer, C., Lawrence, A., Brown, H., Simm, G., 1996. Effect of ewe and lamb genotype on gestation length, lambing ease and neonatal behaviour of lambs. Reproduction, Fertility and Development 8, 1123-1129.

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

Dwyer, C.M., 2014. Maternal behaviour and lamb survival: from neuroendocrinology to practical application. Animal 8, 102-112.

Dwyer, C.M., Bünger, L., 2012. Factors affecting dystocia and offspring vigour in different sheep genotypes. Preventive Veterinary Medicine 103, 257-264.

Dwyer, C.M., Lawrence, A.B., 2005. A review of the behavioural and physiological adaptations of hill and lowland breeds of sheep that favour lamb survival. Applied Animal Behaviour Science 92, 235-260.

Eales, F.A., Gilmour, J.S., Barlow, R.M., Small, J., 1982. Causes of hypothermia in 89 lambs. Veterinary Record 110, 118-120.

Eales, F.A., Small, J., 1985. Effects of acute hypoxia on heat production capacity in newborn lambs. Research in Veterinary Science 39, 212-215.

El-Guindy, M.H., El-Ghannam, F., 1973. Effect of Hysterotomy in ewes at different stages of Gestation on consequent Fertility. Zentralblatt für Veterinärmedizin Reihe A 20, 581-585.

Elliott, J., Sneddon, J., Lee, J.A., Blache, D., 2011. Producers have a positive attitude toward improving lamb survival rates but may be influenced by enterprise factors and perceptions of control. Livestock Science 140, 103-110.

Ennen, S., Scholz, M., Voigt, K., Failing, K., Wehrend, A., 2013. Puerperal development of ewes following dystocia: a retrospective analysis of two approaches to caesarean section. Veterinary Record 172, 554.

Evans, T.J., Rottinghaus, G.E., Casteel, C.W., 2004. Fescue. In: Plumlee, K.H. (Ed.), Clincal Veterinary Toxicology, Mosby, St Louis, MO, pp. 239-243.

Everett-Hincks, J.M., Dodds, K.G., 2008. Management of maternal-offspring behavior to improve lamb survival in easy care sheep systems Journal of Animal Science 86, E259-E270.

Everett-Hincks, J.M., Dodds, K.G., Kerslake, J.I., 2007. Parturition duration and birthing difficulty in twin and triplet lambs. Proceedings of the New Zealand Society of Animal Production 67, 55-60.

Everett-Hincks, J.M., Mathias-Davis, H.C., Greer, G.J., Auvray, B.A., Dodds, K.G., 2014. Genetic parameters for lamb birth weight, survival and death risk traits1. Journal of Animal Science 92, 2885-2895.

Feng, Y., Zhang, P., Zhang, Z., Shi, J., Jiao, Z., Shao, B., 2016. Endocrine disrupting effects of Triclosan on the placenta in pregnant rats. PloS One 11, e0154758.

Ferguson, D.M., Schreurs, N.M., Kenyon, P.R., Jacob, R.H., 2014. Balancing consumer and societal requirements for sheep meat production: an Australasian perspective. Meat Sci 98, 477-483.

Flint, A.P.F., Anderson, A.B.M., Steele, P.A., Turnbull, A.C., 1975. The mechanism by which foetal cortisol controls the onset of parturition in the sheep, Portland Press Limited.

Fogarty, N.M., Thompson, J.M., 1974. Relationship between pelvic dimensions, other body measurements and dystocia in Dorset Horn ewes. Australian Veterinary Journal 50, 502-506.

Fonsêca, V.F.C., Saraiva, E.P., Pimenta Filho, E.C., Furtado, D.A., Mariz, T.M.A., Silva, A.L., Almeida, M.E.V., Pinheiro, A.C., 2014. Influence of the climatic environment and duration of labor on the mother-offspring interaction in Morada Nova sheep. Journal of Animal Science 92, 4123-4129.

Forbes, J.M., 1967. Factors affecting gestation length in sheep. Journal of Agricultural Sciences, Cambridge 68, 191 - 194.

Foster, K., Durmic, Z., Ryan, M., 2019. Maximising the reproductive potential of the meat sheep industry by eliminating high oestrogen clovers, more live lambs on the ground. Meat and Livestock Australia Project P.PSH.1138. Milestone report 3 - 4. Meat and Livestock Australia, Sydney.

Fowden, A.L., Li, J., Forhead, A.J., 1998. Glucocorticoids and the preparation for life after birth: are there long-term consequences of the life insurance? Proceedings of the Nutrition Society 57, 113-122.

Fowler, P.A., Dora, N.J., McFerran, H., Amezaga, M.R., Miller, D.W., Lea, R.G., Cash, P., McNeilly, A.S., Evans, N.P., Cotinot, C., Sharpe, R.M., Rhind, S.M., 2008. In utero exposure to low doses of

environmental pollutants disrupts fetal ovarian development in sheep. Molecular Human Reproduction 14, 269-280.

Friend, M.A., Bhanugopan, M., McGrath, S., Edwards, J.H., Hancock, S., Loudon, K., Miller, D., McGilchrist, P., Refshauge, G., Robertson, S., Masters, D.G., 2020. Do calcium and magnesium deficiencies in reproducing ewes contribute to high lamb mortality? Animal Production Science (in press).

Fthenakis, G.C., 2004. Effects of retention of fetal membranes on subsequent reproductive performance of dairy ewes. Theriogenology 61, 129-135.

Garfield, R.E., Rabideau, S., Challis, J.R., Daniel, E.E., 1979. Hormonal control of gap junction formation in sheep myometrium during parturition. Biology of Reproduction 21, 999-1007.

Geenty, K.G., Brien, F.D., Hinch, G.N., Dobos, R.C., Refshauge, G., McCaskill, M., Ball, A.J., Behrendt, R., Gore, K.P., Savage, D.B., Harden, S., Hocking-Edwards, J.E., Hart, K., van der Werf, J.H.J., 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.

George, J.M., 1976. The incidence of dystocia in Dorset Horn ewes. Australian Veterinary Journal 52, 519-523.

Gilbert, C., Boulton, M., Forsling, M., Goode, J., McGrath, T., 1997. Restricting maternal space during parturition in the pig. Effects on oxytocin, vasopressin and cortisol secretion following vagino-cervical stimulation and administration of naloxone. Animal reproduction science 46, 245-259.

Gore, A.C., Chappell, V.A., Fenton, S.E., Flaws, J.A., Nadal, A., Prins, G.S., Toppari, J., Zoeller, R.T., 2015. EDC-2: The Endocrine Society's Second Scientific Statement on Endocrine-Disrupting Chemicals. Endocrine Reviews 36, E1-E150.

Greenwood, P.L., Hunt, A.S., Hermanson, J.W., Bell, A.W., 1998. Effects of birth weight and postnatal nutrition on neonatal sheep: I. Body growth and composition, and some aspects of energetic efficiency. Journal of Animal Science 76, 2354-2367.

Hall, D., Gilmour, A., Fogarty, N., 1994. Variation in reproduction and production of Poll Dorset ewes. Australian Journal of Agricultural Research 45, 415-425.

Hall, D.G., Fogarty, N.M., Gilmour, A.R., 1995. Performance of crossbred progeny of Trangie Fertility Merino and Booroola Merino rams and Poll Dorset ewes 1. Lamb birth weight, survival and growth. Australian Journal of Experimental Agriculture 35, 1069-1074.

Haughey, K.G., 1973a. Cold injury in newborn lambs. Australian Veterinary Journal 49, 554-563.

Haughey, K.G., 1973b. Vascular abnormalities in the central nervous system associated with perinatal lamb mortality. 1. Pathology. Australian Veterinary Journal 49, 1-8.

Haughey, K.G., 1973c. 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, K.G., 1980a. The effect of birth injury to the foetal nervous system on the survival and feeding behaviour of lambs. In: Wodzicka-Tmaszewska, M., Edey, T.N., Lynch, J.J. (Eds.), Reviews in Rural Science No. IV. University of New England, Armidale.

Haughey, K.G., 1980b. The role of birth in the pathogenesis of meningeal haemorrhage and congestion in newborn lambs. Australian Veterinary Journal 56, 49-56.

Haughey, K.G., 1982. Postnatal mortality, bodyweight gain and wool production to two years of age of lambs surviving caesarean or stressful vaginal birth. Australian Veterinary Journal 58, 173-180.

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

Heap, R.B., Flint, A.P.F., 1984. Pregnancy. In: Austin, C.R., Short, R.V. (Eds.), Reproduction in Mammals: 3. Hormonal Control of Reproduction, Cambridge University Press, Cambridge, UK.

Heap, R.B., Galil, A.K., Harrison, F.A., Jenkin, G., Perry, J.S., 1977. Progesterone and oestrogen in pregnancy and parturition: comparative aspects and hierarchical control. Ciba Foundation Symposium, 127-157.

Henze, P., Bickhardt, K., Fuhrmann, H., Sallmann, H., 1998. Spontaneous pregnancy toxaemia (ketosis) in sheep and the role of insulin. Journal of Veterinary Medicine Series A 45, 255-266.

Herd, R.P., 1965. The relationship between hypocalcaemia and hypomagnesaemia in sheep. Australian Veterinary Journal 41, 385-386.

Higgins, J.P.T., Green, S., 2011. Chapter 4: Guide to the Contents of a Cochrane Protocol and Review. Cochrane Handbook for Systematic Reviews of Interventions Version 5.1.0. The Cochrane Collaboration, pp. 51-79.

Hight, G.K., Jury, K.E., 1970. Hill country sheep production. New Zealand Journal of Agricultural Research 13, 735-752.

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

Hinch, G.N., Davis, G.H., Crosbie, S.F., Kelly, R.W., Trotter, R.W., 1986. Causes of lamb mortality in two highly prolific Booroola crossbred flocks and a Romney flock. Animal Reproduction Science 12, 47-61.

Hindson, J.C., Schofield, B.M., Turner, C.B., 1968. Some factors affecting dilatation of the ovine cervix. Research in Veterinary Science 9, 474 - 480.

Hindson, J.C., Winter, A.C., 2007. Genital abnormalities, obstetrical problems and birth injuries. In: Aitken, I.D. (Ed.), Diseases of Sheep, Blackwell, Oxford, pp. 75-80.

Holmoy, I.H., Waage, S., Granquist, E.G., L'Abee-Lund, T.M., Ersdal, C., Hektoen, L., Sorby, R., 2017. Early neonatal lamb mortality: postmortem findings. Animal 11, 295-305.

Holst, P., Killeen, I., Cullis, B.R., 1986. Nutrition of the pregnant ewe and its effect on gestation length, lamb birth weight and lamb survival. Australian Journal of Agricultural Research 37, 647-655.

Holst, P.J., 2004. Lamb Autopsy: Notes on a procedure for determining cause of death. NSW Agriculture,, Australia.

Holst, P.J., Fogarty, N.M., Hopkins, D.L., Stanley, D.F., 1997. Lamb survival of Texel and Poll Dorset crossbred lambs. Proceedings of the Association for the Advancement of Animal Breeding and Genetics, Dubbo, pp. 313-316.

Holst, P.J., Fogarty, N.M., Stanley, D.F., 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, B.J., Corkrey, R., Hinch, G.N., 2018. Estimation of risk factors associated with difficult birth in ewes. Animal Production Science 58, 1125.

Hoy, D., Brooks, P., Woolf, A., Blyth, F., March, L., Bain, C., Baker, P., Smith, E., Buchbinder, R., 2012. Assessing risk of bias in prevalence studies: modification of an existing tool and evidence of interrater agreement. Journal of Clinical Epidemiology 65, 934-939.

Hughes, K.L., Hartley, W.J., Haughy, K.G., McFarlane, D., 1964. A study of perinatal mortality of lambs from Oberon, Orange and Monaro districts of NSW. Proceedings of Australian Society of Animal Production 5, 92–99.

Jackson, P.G.G., 2004. Chapter 6 - Dystocia in the Ewe. In: Jackson, P.G.G. (Ed.), Handbook of Veterinary Obstetrics (Second Edition), W.B. Saunders, Oxford, pp. 105-124.

Jenkin, G., 1992. Oxytocin and prostaglandin interactions in pregnancy and at parturition. Journal of Reproduction and Fertility. Supplement 45, 97-111.

Jordan, D., Le Feuvre, A., 1989. The extent and cause of perinatal lamb mortality in 3 flocks of Merino sheep. Australian Veterinary Journal 66, 198-201.

Kenyon, P.R., Roca Fraga, F.J., Blumer, S., Thompson, A.N., 2019. Triplet lambs and their dams – a review of current knowledge and management systems. New Zealand Journal of Agricultural Research 62, 399-437.

Kerslake, J.I., Everett-Hincks, J.M., Campbell, A.W., 2005. Lamb survival: A new examination of an old problem. Proceedings of the New Zealand Society of Animal Production 65, 13-18.

Kilgour, R.J., Haughey, K.G., 1993. Pelvic size in Merino ewes selected for lamb-rearing ability is greater than that of unselected Merino ewes. Animal Reproduction Science 31, 237-242.

Kitts, D.D., Anderson, G.B., Bon Durant, R.H., Kindahl, H., Stabenfeldt, G.H., 1985. Studies on the endocrinology of parturition: relative steroidogenesis in coexisting genetically dissimilar ovine fetuses, concomitant with the temporal patterns of maternal C18 and C19 steroids and prostaglandin F2 alpha release. Biology of Reproduction 33, 67-78.

Kitts, D.D., Anderson, G.B., BonDurant, R.H., Stabenfeldt, G.H., 1984. Temporal patterns of Δ4 C-21 steroids in coexisting, genetically dissimilar twin lamb fetuses throughout late gestation. Endocrinology 114, 703-711.

Knight, T.W., Lynch, P.R., Hall, D.R.H., Hockey, H.-U.P., 1988. Identification of factors contributing to the improved lamb survival in Marshall Romney sheep. New Zealand Journal of Agricultural Research 31, 259-271.

Lane, J., Jubb, T., Shephard, R., Webb-Ware, J., Fordyce, G., 2015. Priority list of endemic diseases for the red meat industries. Meat and Livestock Australia, North Sydney.

Lashley, V.D., Roe, W.D., Kenyon, P.R., Thompson, K.G., 2014. Perinatal lamb mortality: an assessment of gross, histological and immunohistochemical changes in the central nervous system. New Zealand Veterinary Journal 62, 160-166.

Laster, D.B., 1974. Factors Affecting Pelvic Size and Dystocia in Beef Cattle. Journal of Animal Science 38, 496-503.

Lean, I.J., DeGaris, P.J., Celi, P., McNeill, D.M., Rodney, R.M., Fraser, D.R., 2014. Influencing the future: interactions of skeleton, energy, protein and calcium during late gestation and early lactation. Animal Production Science 54, 1177-1189.

Ledgert, W.L., Ellwood, D.A., Taylor, M.J., 1983. Cervical softening in late pregnant sheep by infusion of prostaglandin E-2 into a cervical artery. Reproduction 69, 511-515.

Leontides, L., Fthenakis, G.C., Amiridis, G.S., Saratsis, P., 2000. A matched case-control study of factors associated with retention of fetal membranes in dairy ewes in Southern Greece. Preventive Veterinary Medicine 44, 113-120.

Lewis, C.J., 2007. Clostridial diseases. In: Aitken, I. (Ed.), Diseases of Sheep, Blackwell, Oxford, pp. 156-167.

Li, L., Brown, D.J., 2016. Estimation of genetic parameters for lambing ease, birthweight and gestation length in Australian sheep. Animal Production Science 56, 934-940.

Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gotzsche, P.C., Ioannidis, J.P., Clarke, M., Devereaux, P.J., Kleijnen, J., Moher, D., 2009. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. Journal of Clinical Epidemiology 62, e1-34.

Liggins, G.C., 1982. The fetus and birth. In: R., A.C., Short, R.V. (Eds.), Reproduction in Mammals: 2. Embryonic and Fetal Development, Cambridge University Press, Cambridge, UK, pp. 114 - 141.

Liggins, G.C., Thorburn, G.D., 1994. Initiation of parturition. In: Lamming, G.E. (Ed.), Marshall's Physiology of Reproduction, Chapman and Hall, London, UK, pp. 863-1002.

Lockwood, A., Hancock, S., Kearney, G., Thompson, A., 2019a. Reducing mob size increases the survival of twin-born Merino lambs when feed-on-offer from pasture is limited and ewes are supplementary fed during lambing. Small Ruminant Research 173, 65-69.

Lockwood, A., Hancock, S., Paganoni, B., Macleay, C., Kearney, G., Sohi, R., Thompson, A., 2019b. Mob size of single-bearing or twin-bearing Merino ewes at lambing may not influence lamb survival when feed-on-offer is high. animal 13, 1311-1318.

Luff, A., 1980. A service for all seasons. The success story of the Sheep Fertility Service at Wagga NSW. Wool Research Development

Lundh, T., 1995. Metabolism of estrogenic isoflavones in domestic animals. Proceedings of the Society for Experimental Biology and Medicine 208, 33-39.

Marret, S., Doyle, L.W., Crowther, C.A., Middleton, P., 2007. Antenatal magnesium sulphate neuroprotection in the preterm infant. Seminars in Fetal & Neonatal Medicine 12, 311-317.

Massmann, G.A., Zhang, J., Figueroa, J.P., 1999. Functional and molecular characterization of nitric oxide synthase in the endometrium and myometrium of pregnant sheep during the last third of gestation. American Journal of Obstetrics and Gynecology 181, 116-125.

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

Masters, D.G., Norman, H.C., Thomas, D.T., 2019. Minerals in pastures—are we meeting the needs of livestock? Crop and Pasture Science, Online.

Matheson, S.M., Bunger, L., Dwyer, C.M., 2012. Genetic parameters for fitness and neonatal behavior traits in sheep. Behavioural Genetics 42, 899-911.

Mathias-Davis HC, Yuan YV, JM., E.-H., 2010. Effect of litter weight variation on cause of death and survival in triplet lambs. Proceedings of the New Zealand Society of Animal Production 70, 175-179.

Mavrogianni, V.S., Brozos, C., 2008. Reflections on the causes and the diagnosis of peri-parturient losses of ewes. Small Ruminant Research 76, 77-82.

Maxwell, J.A., 1970. Field observations on four outbreaks of maternal dystocia in the Merino ewe. Australian Veterinary Journal 46, 533-536.

McCutcheon, S.N., Holmes, C.W., McDonald, M.F., 1981. The starvation-exposure syndrome and neonatal lamb mortality. A review. Proceedings of the New Zealand Society of Animal Production.

McDonald, J.W., 1966. Variation in perinatal mortality of lambs with age and parity of ewes. Proceedings Australian Society of Animal Production 6, 60-62.

McFarlane, D., 1965. Perinatal lamb losses. 1. An autopsy method for the investigation of perinatal losses. New Zealand Veterinary Journal 13, 116-135.

McGrath, S.R., Lievaart, J.J., Friend, M.A., 2013a. Extent of utilisation of dual-purpose wheat for grazing by late-pregnant and lambing ewes and producer-reported incidence of health issues in southern New South Wales. Australian Veterinary Journal 91, 432-436.

McGrath, S.R., Lievaart, J.J., Virgona, J.M., Bhanugopan, M.S., Friend, M.A., 2013b. Factors involved in high ewe losses in winter lambing flocks grazing dual-purpose wheat in southern New South Wales: a producer survey. Animal Production Science 53, 458-463.

McHugh, J.F., Edwards, M.S.H., 1958. Lamb loss investigations at Rutherglen station. Journal of the Department of Agriculture Victoria 56, 425.

McHugh, N., Berry, D.P., Pabiou, T., 2016. Risk factors associated with lambing traits. Animal 10, 89-95.

McLean, J.W., 1956. Vaginal prolapse in sheep. New Zealand Veterinary Journal 4, 38-55.

McMillan, W.H., 1983. Hogget lamb mortality. Proceedings of the New Zealand Society of Animal Production.

McMillen, I., Phillips, I., Ross, J., Robinson, J., Owens, J., 1995. Chronic stress--the key to parturition? Reproduction, Fertility and Development 7, 499-507.

McQuillan, M., Glanville, E., Jacobson, C., Sherriff, L., Whale, A., 2019. Unlocking the keys to ewe survival (miletsone 3 - interim report project L.LSM.0019. North Sydney.

McSporran, K.D., Fielden, E.D., 1979. Studies on dystocia in sheep II: Pelvic measurements of ewes with histories of dystocia and eutocia. New Zealand Veterinary Journal 27, 75-78.

Mee, J.F., 2008. Prevalence and risk factors for dystocia in dairy cattle: a review. Vet J 176, 93-101.

Mellor, D.J., Stafford, K.J., 2004. Animal welfare implications of neonatal mortality and morbidity in farm animals. The Veterinary Journal 168, 118-133.

Menzies, P.I., 2006. Lambing Management and Neonatal Care. Saunders Elsevier, pp. 680-695.

Meyer, A.M., Reed, J.J., Neville, T.L., Taylor, J.B., Hammer, C.J., Reynolds, L.P., Redmer, D.A., Vonnahme, K.A., Caton, J.S., 2010. Effects of plane of nutrition and selenium supply during gestation on ewe and neonatal offspring performance, body composition, and serum selenium. J. Anim Sci. 88, 1786-1800.

Moore, R.W., McDonald, I.M., Messenger, J.J., 1966. Fox predation as a cause of lamb mortality. Proceedings of Australian Society of Animal Production 6, 157-160.

Morris, G.A.M., 1973. The performance of the Merino ewe and lamb as influenced by nutrition during pregnancy., University of New England, Armidale, NSW, Australia.

Morrison, D.G., Williamson, W.D., Humes, P.E., 1986. Estimates of Heritabilities and Correlations of Traits Associated with Pelvic Area in Beef Cattle. Journal of Animal Science 63, 432-437.

Mosdoel, G., 1987. Indications for and fertility after caesarean section in the ewe in common practice. Norsk Veterinaertidsskrift 98, 441-444.

Mostefai, E., Kouidri, M., Selles, S.M.A., 2019. Causes of sheep dystocia in Djelfa area (Algeria). Revue Marocaine des Sciences Agronomiques et Veterinaires 7, 284-287.

Moule, G.R., 1961. The fertility of sheep grazing oestrogenic pastures. The Australian Veterinary Journal 37, 109-114.

Moulk, G.R., 1954. Observations on mortality amongst lambs in Queensland. Australian Veterinary Journal 30, 153-171.

Munn, Z., Moola, S., Lisy, K., Riitano, D., Tufanaru, C., 2015. Methodological guidance for systematic reviews of observational epidemiological studies reporting prevalence and cumulative incidence data. Int J Evid Based Healthc 13, 147-153.

Murphy, P.M., Lindsay, D.R., 1996. The contribution of the activity of the newborn Merino lamb to the attachment to its mother and subsequent survival., Proceedings of the Australian Society of Animal Production. The Australian Society of Animal Production, p. 486.

Mutinati, M., Pantaleo, M., Roncetti, M., Piccinno, M., Rizzo, A., Sciorsci, R.L., 2014. Oxidative stress in neonatology. A review. Reproduction in Domestic Animals 49, 7-16.

Naaktgeboren, C., 1979. Behavioural aspects of parturition. Animal Reproduction Science 2, 155-166.

Naaktgeboren, C., Bontekoe, E.H.M., 1976. Vergleichend-geburtskundliche Betrachtungen und experimentelle Untersuchungen über psychosomatische Störungen der Schwangerschaft und des Geburtsablaufes. Zeitschrift für Tierzüchtung und Züchtungsbiologie 93, 264-320.

Naaktgeboren, C., Slijper, E.J., 1970. Biologie der Geburt: eine Einführung in die vergleichende Geburtskunde, Parey.

Neumann, I.D., Johnstone, H.A., Hatzinger, M., Liebsch, G., Shipston, M., Russell, J.A., Landgraf, R., Douglas, A.J., 1998. Attenuated neuroendocrine responses to emotional and physical stressors in pregnant rats involve adenohypophysial changes. The Journal of Physiology 508, 289-300.

O'Connor, D., Green, S., Higgins, J.P.T., 2011. Chapter 5: Defining the review question and developing criteria for including studies. In: Higgins, J.P.T., Green, S. (Eds.), Cochrane Handbook of Systematic Reviews of Intervention. Version 5.1.0 (updated March 2011). The Cochrane Collaboration.

Oliver, M.H., Harding, J.E., Gluckman, P.D., 2001. Duration of maternal undernutrition in late gestation determines the reversibility of intrauterine growth restriction in sheep. Prenatal and Neonatal Medicine 6, 271-279.

Osuagwuh, A.I.A., Taiwo, B.B.A., Ngere, L.O., 1980. Crossbreeding in tropical sheep: Incidence of dystocia and parturition losses. Tropical Animal Health and Production 12, 85-89.

Owiny, J., Fitzpatrick, R., 1990. Effect of intravaginal application of prostaglandin E2 gel on the mechanical properties of the ovine cervix uteri at term. American Journal of Obstetrics and Gynecology 163, 657 - 660.

Paterni, I., Granchi, C., Minutolo, F., 2017. Risks and benefits related to alimentary exposure to xenoestrogens. Critical Reviews in Food Science and Nutrition 57, 3384-3404.

Patil, A.S., Rathod, R., Nagaraja, B.N., 2014. Retrospective studies on occurence of dystocia and it's management in domestic animals. Intas Polivet 15, 269+.

Paul, C., Rhind, S.M., Kyle, C.E., Scott, H., McKinnell, C., Sharpe, R.M., 2005. Cellular and hormonal disruption of fetal testis development in sheep reared on pasture treated with sewage sludge. Environmental Health Perspectives 113, 1580 - 1587.

Pethick, D.W., Harper, G.S., Dunshea, F.R., 2005. Fat metabolism and turnover. In: Dijkstra, J., Forbes, J.M., France, J. (Eds.), Quantitative Aspects of Ruminant Digestion and Metabolism, CAB International, pp. 345-371.

Plush, K.J., Brien, F.D., van Wettere, W.H.E.J., Hynd, P.I., 2016. Preparing the neonate for the transition from intra-uterine to extra-uterine life. Proceedings of the 31st Biennial Conference of the Australian Society of Animal Production, Adelaide, South Australia, p. Ref No. 1415.

Porter, J.K., Thompson, F.N., Jr., 1992. Effects of fescue toxicosis on reproduction in livestock. Journal of Animal Science 70, 1594-1603.

Prasad, V.D., Sreenu, M., Kumar, R.V.S., Rao, T.S.C.S., Srilatha, C., 2014. A retrospective study of aetiologies of dystocia in small ruminants. Intas Polivet 15, 284+.

Redmer, D.A., Wallace, J.M., Reynolds, L.P., 2004. Effect of nutrient intake during pregnancy on fetal and placental growth and vascular development. Domestic Animal Endocrinology 27, 199-217.

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

Refshauge, G., Earney, H., Doyle, E., Kermode, H., Holman, B.W.B., 2018a. Macroscopic assessment and meningeal brain colour in autopsied neonatal lambs. 32nd Proceedings of the Australia Society of Animal Production, p. 32.

Refshauge, G., Earney, H., Doyle, E., Kermode, H., Holman, B.W.B., 2018b. The meningeal colour of different categories of death in neonatal lambs. 32nd Proceedings of the Australia Society of Animal Production, p. 33.

Refshauge, G., Earney, H., Doyle, E., Kermode, H., Holman, B.W.B., 2018c. Quantifying the colour of meningeal lesions of the brain in autopsied neonatal lambs. 32nd Proceedings of the Australia Society of Animal Production, p. 31.

Risco, C.A., Reynolds, J.P., Hird, D., 1984. Uterine prolapse and hypocalcemia in dairy cows. Journal of the American Veterinary Medical Association 185, 1517-1519.

Rizzo, A., Mutinati, M., Spedicato, M., Minoia, G., Trisolini, C., Jirillo, F., Sciorsci, R.L., 2008. First demonstration of an increased serum level of reactive oxygen species during the peripartal period in the ewe. Immunopharmacology and Immunotoxicology 30, 741-746.

Robalo Silva, J., Noakes, D.E., 1984. The effect of experimentally induced hypocalcaemia on uterine activity at parturition in the ewe. Theriogenology 21, 607-623.

Robertson, S.M., Friend, M.A., Doran, G.S., Edwards, S., 2017. Caffeine supplementation of ewes during lambing may increase lamb survival. Animal 12, 376-382.

Roger, P., 2009. Problems of the postparturient ewe. In Practice 31, 122.

Rosselli, M., Reinhart, K., Imthurn, B., Keller, P.J., Dubey, R.K., 2000. Cellular and biochemical mechanisms by which environmental oestrogens influence reproductive function. Human Reproduction Update 6, 332-350.

Rüsse, M., 1963. Der Geburtsablauf beim Rind: eine Betrachtung des funktionellen Geschehens bei der Normalgeburt.

Sargison, N.D., West, D.M., Clark, R.G., 1997. An investigation of the possible effects of subclinical iodine deficiency on ewe fertility and perinatal lamb mortality. New Zealand Veterinary Journal 45, 208.

Sargison, N.D., West, D.M., Clark, R.G., 1998. The effects of iodine deficiency on ewe fertility and perinatal lamb mortality. New Zealand Veterinary Journal 46, 72-75.

Scales, G.H., Burton, R.N., Moss, R.A., 1986. Lamb mortality, birthweight, and nutrition in late pregnancy. New Zealand Journal of Agricultural Research 29, 75-82.

Scott, P., 2011. Uterine torsion in the ewe. Livestock 16, 37-39.

Selye, H., 1956. The stress of life.

Shutt, D.A., Cox, R.I., 1972. Steroid and phyto-oestrogen binding to sheep uterine receptors in vitro. Journal of Endocrinology 52, 299-310.

Silva, R., Noakes, D., 1984. The effect of experimentally induced hypocalcaemia on uterine activity at parturition in the ewe. Theriogenology 21, 607-623.

Sirinivas, M., Sreenu, M., 2009. A retrospective study on assisted lambings. Veterinary Practitioner 10, 81-83.

Smalley, H.E., Curtis, J.M., Earl, F.L., 1968. Teratogenic action of carbaryl in beagle dogs. Toxicology and Applied Pharmacology 13, 392-403.

Smith, G.M., 1977. Factors Affecting Birth Weight, Dystocia and Preweaning Survival in Sheep. Journal of Animal Science 44, 745-753.

Smith, I.D., 1962. Reproductive wastage in a Merino flock in central western Queensland. Australian Veterinary Journal 38, 500-507.

Smith, I.D., 1964. Ovine neonatal mortality in western Queensland. Proceedings of Australian Society of Animal Production 5, 100-106.

Speijers, M.H., Carson, A.F., Dawson, L.E., Irwin, D., Gordon, A.W., 2010. Effects of sire breed on ewe dystocia, lamb survival and weaned lamb output in hill sheep systems. Animal 4, 486-496.

Stephenson, R.G.A., Suter, G.R., Le Feuvre, A.S., 1984. Reduction of the effects of heat stress on lamb birth weight and survival by provision of shade. Reproduction in sheep: Australian Wool Corporation technical publication/supervising editors, DR Lindsay and DT Pearce.

Stevens, D., Alexander, G., Bell, A.W., 1990. Effect of prolonged glucose infusion into fetal sheep on body growth, fat deposition and gestation length. Journal of Developmental Physiology 13, 277-281.

Suttle, N.F., 2010. Mineral nutrition of livestock, CABI Publishing, Wallingford.

Taylor, S.C.S., Monteiro, L.S., Perreau, B., 1975. Possibility of reducing calving difficulties by selection. III - A note on pelvic size in relation to body weight of cattle. Genetics Selection Evolution 7, 49-57.

Thomas, J.O., 1990. Survey of the causes of dystocia in sheep. Veterinary Record 127, 574-575.

Tribe, R.M., 2001. Regulation of human myometrial contractility during pregnancy and labour: are calcium homeostatic pathways important? Experimental Physiology 86, 247-254.

Trompf, J., Young, J., Bowen, E., 2018. Review of National Sheep Reproduction and Lamb Survival

Trompf, J.P., Gordon, D.J., Behrendt, R., Curnow, M., Kildey, L.C., Thompson, A.N., 2011. Participation in Lifetime Ewe Management results in changes in stocking rate, ewe management and reproductive performance on commercial farms. Animal Production Science 51, 866-872.

Tzora, A., Leontides, L.S., Amiridis, G.S., Manos, G., Fthenakis, G.C., 2002. Bacteriological and epidemiological findings during examination of the uterine content of ewes with retention of fetal membranes. Theriogenology 57, 1809-1817.

Upton, W.H., Bunter, K.L., 1995. Pelvic measurement as an aid to selection in beef cattle. Proceedings of the Association for the Advancement of Animal Breeding and Genetics, p. 615.

Usui, T., Ikeda, Y., Tagami, T., Matsuda, K., Moriyama, K., Yamada, K., Kuzuya, H., Kohno, S., Shimatsu, A., 2002. The phytochemical lindleyin, isolated from Rhei rhizoma, mediates hormonal effects through estrogen receptors. Journal of Endocrinology 175, 289 - 296.

Verbeek, E., Oliver, M.H., Waas, J.R., McLeay, L.M., Blache, D., Matthews, L.R., 2012. Reduced cortisol and metabolic responses of thin ewes to an acute cold challenge in mid-pregnancy: implications for animal physiology and welfare. PloS One 7.

Viechtbauer, W., 2010. Conducting Meta-Analyses in R with the metafor Package. 2010 36, 48.

Waage, S., Wangensteen, G., 2009. Outcomes of ewes and their offspring following caesarian section., 7th International Sheep Veterinary Congress, Stavanger, p. 127.

Waage, S., Wangensteen, G., 2013. Short-term and long-term outcomes of ewes and their offspring after elective cesarean section. Theriogenology 79, 486-494.

Walker, S.K., Kleemann, D.O., Bawden, C.S., 2002. Sheep reproduction in Australia: Current status and potential for improvement through flock management and gene discovery Meat and Livestock Australia. In: Australia, M.a.L. (Ed.), Meat and Livestock Australia.

West, H.J., 1996. Maternal undernutrition during late pregnancy in sheep. Its relationship to maternal condition, gestation length, hepatic physiology and glucose metabolism. British Journal of Nutrition 75, 593-605.

Whittlestone, W.G., 1954. The effect of adrenaline on the milk-ejection response of the sow. Journal of Endocrinology 10, 167-172.

Woclawek-Potocka, I., Bah, M.M., Korzekwa, A., Piskula, M.K., Wiczkowski, W., Depta, A., Skarzynski, D.J., 2005. Soybean-derived phytoestrogens regulate prostaglandin secretion in endometrium during cattle estrous cycle and early pregnancy. Experimental Biology and Medicine 230, 189-199.

Wocławek-Potocka, I., Mannelli, C., Boruszewska, D., Kowalczyk-Zieba, I., Waśniewski, T., Skarżyński, D.J., 2013. Diverse effects of phytoestrogens on the reproductive performance: cow as a model. International Journal of Endocrinology 2013.

Woolliams, C., Wiener, G., Macleod, N.S.M., 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, J.M., Trompf, J., Thompson, A.N., 2014. The critical control points for increasing reproductive performance can be used to inform research priorities. Animal Production Science 54, 645-655.

Zaborski, D., Grzesiak, W., Szatkowska, I., Dybus, A., Muszynska, M., Jedrzejczak, M., 2009. Factors affecting dystocia in cattle. Reproduction in Domestic Animals 44, 540-551.

Appendix 1: Classification of cause of death and interpretation of lesions at necropsy

A robust system to classify cause of death via necropsy is important in determining the role and seriousness of birth injuries. The development of comprehensive neonatal lamb autopsy procedures commenced with the method proposed by McFarlane (1965). This method created three broad categories centred on the time of birth; ante-parturient, parturient and post-parturient. Evidence of tissue autolysis and other signs of viability underpin the classification, such as the presence of oedema, aeration of lung tissue, evidence of walking, the metabolism of perirenal or pericardial brown adipose tissue and the presence of colostrum in the abomasum.

A further separation of categories relies on the subjective assessment of macroscopic lesions of the meninges, spinal column and spinal cord. While McFarlane (1965) alluded to the presence of such lesions, no further description was provided nor was their inclusion in the categorisation to determine cause of death.

Haughey (1973b) modified the procedure and emphasised the examination of the central nervous system. That work revealed blood clots and congestion were often identified over the cerebral hemispheres, epidural haemorrhages were found typically around the atlanto-occipital joint and blood-stained cerebrospinal fluid were observed around the cervical vertebral region. Subsequent studies found injury to the central nervous system was common to a majority of dead lambs (Haughey, 1973c; 1980b; Duff et al., 1982).

A system to subjectively rank the severity of central nervous system lesions was proposed by (Holst, 2004). Applying the severity scale to the brain, spinal cord and vertebral canal of newborn lambs requires a subjective assessment of the size and number of blood clots, haemorrhages and congestion. Assessment of congestion can be made by considering the deepening coloration of meningeal tissues from light pink colours through to reds and to purple. As with all subjective assessments, bias and drift will be problematic and assessors have to rely on the written descriptions and few photographic examples to make a judgment (e.g. Holst (2004)).

Recent Australian autopsy studies relying on lesion scoring suggest that between 48% (Refshauge et al., 2016) and 67% of autopsied lambs (Holst et al., 2002) had died from a form of dystocia. Not all research has made observations in support of the relationships between central nervous system injury and cause of death (Lashley et al., 2014). Those authors suggest the vascular changes may be artefacts of poor handling. The methods employed in that study did not follow the classification proposed by Holst (2004), but did rely on the descriptions provided by Haughey (1973c). Most lambs that died naturally did not have any lesions (75%), yet all of the lambs that were sacrificed did have lesions. Examining lambs that had subcutaneous oedema from a difficult birth, only 1/3 displayed moderate meningeal haemorrhage. Most lambs were classified as SME (Lashley et al., 2014) and little distinction between dystocia and SME could be determined when assessing central nervous system lesions and their histopathology was unable to associate hypoxia/ischemia with evidence of SME. To the time of writing, the study by Lashley et al. (2014) stands alone for its contrasting findings. The absolute relationship between lesion scores and lamb mortality was also questioned by Alexander (1984). The article by the latter author requires careful reading and has been discussed elsewhere (Refshauge et al., 2016).

Further comprehensive studies are required to understand more about the importance of the assessment of the central nervous system to neonatal mortality. Preliminary studies examining brain surface colour show some promise (Refshauge et al., 2018c, a, b). The aims of such studies were to objectify lesion severity scores. Earlier Haughey (1980b) reported that 7% of lambs born via caesarean-section had meningeal haemorrhages, which remains unexplained. A possible explanation may be that in some instances the lungs of neonates fail to inflate properly leading to post-partum hypoxia and meningeal lesions. This is an area of research that warrants further research.

Appendix 2: Methodology for the systematic review

Research question, definitions, protocol and search strategy

A systematic review was conducted to estimate the proportion lamb mortality attributable to dystocia (proportional mortality ratio) in Australia and New Zealand. The systematic review protocol was developed based on the Cochrane guidelines (Higgins and Green, 2011), and the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) statement (Liberati et al., 2009), with specific modifications for a systematic review reporting measures of disease frequency, as recommended by the Joanna Briggs Institute (Munn et al., 2015).

Definition of death due to dystocia

To calculate the proportional mortality ratio for dystocia in each study, the total number of dystocia cases were included. Lamb mortality due to dystocia was based on McFarlane (1965) and Holst (2004) and was defined as: a lamb that has undergone post-mortem examination and has one or more of the following features:

- The presence of subcutaneous oedema typically around the head and neck. A lamb that is unviable after birth but would have been viable if not for foeto-pelvic disproportion or malpresentation
- Stillborn lambs with significant lesion scores (Score 3-5 on a 1-5 point scale at both the cranial-meningeal and the spinal-CNS assessment sites) and had not metabolised perirenal or pericardial fat. These lambs could have breathed and walked, but must have died at a time very close to the time of birth so as to not require heat production from their thermogenic brown fat reserves.
- Lambs dying due to birth injury had significant lesion scores, had breathed and had metabolised perirenal and pericardial fat reserves. These lambs died at any time up to 5 days after their birth. In some cases, lambs may have ingested some milk, but it is the presence of significant lesion scores that defines this death category.

Eligibility criteria

The records identified in the search were assessed for eligibility using the PICOS approach (P: population; I: the intervention or exposure; C; the comparator group; O: outcome or endpoint; S: the study designs chosen) (O'Connor et al., 2011) (Table 14). Sheep in Australia and New Zealand were the population of interest and for this study all breeds were included. The exposure of interest was death due to dystocia as defined in the case definition (see above). The comparator group were lambs with no evidence of dystocia on post-mortem examination. A variety of observations made during post-mortem examination were used to determine the exposure, therefore the classification system used by the researchers was recorded in the data extraction form. Randomised control trials, cohort studies, case-control studies, cross-sectional studies, case reports and outbreak investigations were all included if they reported number of post-mortems conducted (denominator) and the number of animals classified as death due to dystocia (numerator).

Table 14. Descriptions of the population, exposure, outcome, study types and limits used as inclusion criteria for estimating proportional mortality ratio

Population	The study population includes sheep of all breeds in Australia and New Zealand.
Exposure	Dystocia (see case definitions of dystocia)
Comparison	Lambs with no evidence of dystocia on post mortem examination
Outcome	Perinatal or post-natal lamb mortality
Studies	Original research papers: experimental, case-control, cohort, cross-sectional studies, case reports or outbreak investigations where infected and non-infected animals are compared.
Limits	Restrictions on date of publication (published after 1st January 1990)
	Language: No restriction
	Document type: all document types were included.

Search strategy

A systematic search of four databases was conducted on the 11th of January 2020: (i) PubMed; (ii) Web of Science – All Databases; (iii) Scopus; and (iv) Cochrane. The following search terms used:

sheep OR ovine OR "small ruminant"
AND
(lamb AND survival) OR dystocia OR (lamb AND mortality) OR (lambing AND ease) OR stillbirth OR parturition
AND
Australia OR "New Zealand" OR Australasia

The search terms were developed by the research team and refined in consultation with the veterinary and life sciences librarian at Murdoch University. Because of the changes in methods of classifying dystocia from a post-mortem examination, we only included studies published since 1st January 1990 with the aim to review data that was more consistent in measurement. We included studies that reported all categories of dystocia (as outlined in Appendix 1) and recorded the classification system used.

EndNote X9 (Thompson Reuters) bibliographic software was used to manage citations. Duplicate entries were identified, using the automatic function in EndNote and manually during the screening process, by considering the author, the year of publication, the article title, and the volume, issue and page numbers of the source. In questionable cases, the full-text articles were compared. Conference abstracts of studies that were subsequently published in journals were considered duplicates.

Screening

The records identified were assessed for eligibility in two phases (Figure 5). The initial screening was conducted by one researcher (MB), who screened references by titles, available abstracts, or both as required to determine the relevance of the study, and references that did not fulfil the eligibility criteria were excluded from the review. Papers not immediately identifiable as fitting either the inclusion or the exclusion criteria were kept for full text screening. If the abstract was not available and the title was not sufficiently clear to satisfy the exclusion criteria, the reference was included for full-text screening. Following the first screening process, the full text of each selected article was retrieved for detailed analysis and subject to a second screening to eliminate any that did not fulfill the eligibility criteria described above.

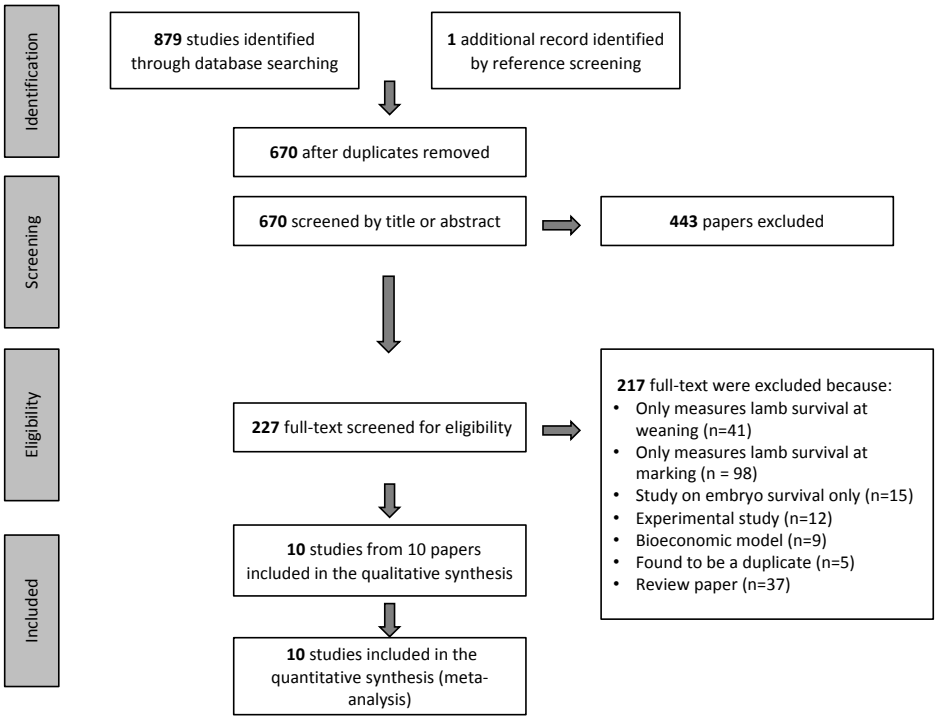

Figure 5. Flow diagram detailing the study selection process for the systematic review on proportional mortality ratio for dystocia in lambs in Australia and New Zealand

Data extraction and quality assessment

Data extraction was performed by one reviewer (MB) and checked for accuracy by CJ. Any ambiguous information was discussed and variable values recorded by consensus. The data extracted included: (i) study characteristics (authors, year or years the study was conducted, study design, geographical location, *a priori* objectives, sample size calculations and funding sources); (ii) animal characteristics (breed of ewe and sire, age of ewe, parity of ewe, age of lamb, birth type); (iii) numerator case definition, namely the post-mortem protocol; (iv) definition of a suitable comparator (for example death due to SME); and (v) the total number of animals that underwent post-mortem examination (denominator) and number in each exposed and non-exposed group

(numerator). One reviewer (MB) conducted the quality assessment using a risk of bias tool as described by Hoy et al. (2012), modified for proportional mortality ratio. Each study was assigned an overall quality score between 0 and 10.

Data analysis

The primary outcome measure is proportion of lamb mortality attributable to dystocia. Summary tables of extracted data were created to describe the characteristics and findings of the included studies. Pooled effect sizes were calculated and associated forest plots created. An assessment of between-study heterogeneity was conducted by examining the forest plots and the I^2. Statistical analyses were performed in R statistical software using the "meta"(Balduzzi et al., 2019), "metafor"(Viechtbauer, 2010), and "weightr"(Coburn and Vevea, 2019) packages. Pooled analysis of proportions (dystocia) were calculated using the methods described by Munn et al (2015), weighted summary proportion under random effects model. Subgroup analysis was conducted to investigate differences in proportional mortality ratios for dystocia in lambs born to Merino ewes compared to cross-breed ewes or other breeds, and between birth type (single, twin, triplet or more).