



THE UNIVERSITY OF
SYDNEY

**Walk over weighing in Poll Dorset sheep: ewe and lamb
liveweight, growth rate, and lamb survival across
reproductive stages**

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A thesis submitted in fulfilment of the requirements for the
degree of Doctor of Philosophy the Faculty of Science from the
University of Sydney

2026

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Research Work and Authorship

This thesis includes 4 original chapter (papers) that have not been published. These chapters have been formatted as per the University of Sydney thesis guidelines and are presented as such. Chapters 3 to 6 are therefore stand-alone manuscripts, each with its own abstract, introduction, materials and methods, results, discussion, conclusion, acknowledgments and references. The research ideas, organisation, analysis and writing of all chapters in this thesis were the principal responsibility of the candidate, Gregory Sawyer, working independently under the supervision of Professor Luciano Gonzalez and Dr Augusto Imaz at The University of Sydney. I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and resources have been acknowledged.

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Publications

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Dedication

To those who dared to dream with me, stood by me, and helped me turn persistence into progress - this is for you. To the quiet voices that cheered me on when I couldn't hear my own – thank you, always and forever.

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Declaration

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where stated otherwise, by reference or acknowledgment, the work presented is entirely my own.

Name: Gregory John Lynn Sawyer

As the primary supervisor for the candidature, I can confirm that the authorship attribution statement above is correct.

Luciano Adrián González

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List of Abbreviations

%Dev - Percentage Deviation

ADG – Average Daily Gain

ASBV – Australian Sheep Breeding Values

Adj R² - Adjusted R Squared

ANOVA - Analysis of Variance

BCS - Body Condition Score C_b – Bias Correction Factor

CCC – Lin’s Concordance Correlation Coefficient

Df – Degrees of freedom

EID – Electronic Ear Tag Identification

GLM - Generalised Linear Models

GNSS - Global Navigation Satellite System

GWT – Greasy Wool Weight

kg – Kilogram

kg/d – Kilogram per day

kg/hd – Kilogram per head

LM - Linear Models

LW - Liveweight

MM – Mathematical Models

MSEP – Mean Square Error of Prediction

n - Sample size

$Q(\chi^2)$ - Chi-square

PA - Precision Agriculture

PLF - Precision Livestock Farming

r - Pearson correlation coefficient

r^2 - Coefficient of Determination

R- Response variables

RFID - Radio Frequency Identification

RMSE – Root Mean Square Error

SD - Standard deviation

SE - Standard error

SLS – Scanned Litter Size

TLWW – Total Litter Weight Weaned

WOW – Walk Over Weighing Platform

WLS - Weaned Litter Size

YW – Yard Weight

Abstract

The present thesis investigated the application of walk-over-weighing (WOW) technology as a precision livestock farming (PLF) tool to improve monitoring and management in grazing Australian sheep production systems. The research integrated technological evaluation with biological modelling, focusing on reproductive performance, early-life growth, and lamb survival under commercial grazing conditions.

Chapter 3 evaluated WOW accuracy against conventional yard weighing (YW) using 5,786 paired observations collected under commercial conditions. A strong linear association between WOW and YW was identified ($R^2 = 0.89$; RMSE = 7.73 kg; Lin's concordance correlation coefficient = 0.98), with significant mean bias of -2.84 kg and systematic bias ($P < 0.05$) potentially due to the effect of mustering and handling animals in the yards. Random error accounted for 81.95% of prediction error. The WOW technology and associated data processing using penalised B-splines and outlier detection is suitable to monitor liveweight (LW) in commercial flocks.

Chapter 4 applied WOW to monitor the effect of reproductive performance on LW of 315 artificially inseminated Poll Dorset ewes across two lactations. Mixed-effects models identified significant scanned litter size (SLS) \times date interactions for LW in both years ($P < 0.05$) and average daily gain (ADG) in one of the years ($P < 0.001$) but not the other year ($P > 0.05$). Although differences were not consistent between years, twin bearing ewes were heavier in late gestation, lost more LW during early lactation and showed slower recovery of LW in late lactation compared to single bearing ewes. This chapter demonstrated the ability of WOW technology to detect biologically meaningful variation in ewe LW and ADG across reproductive stages, which offer applications to manage LW timelier and more accurately under commercial conditions.

Chapter 5 extended the use of WOW to monitor lamb performance analysing LW and ADG of 830 lambs at foot across three years (2020–2022). Significant weaned litter size (WLS) \times date interactions were identified in 2020 and 2022 ($P < 0.05$), with triplets showing lower LW and ADG compared to

single and twin lambs. Therefore, this chapter supported the use of WOW technology as a non-invasive tool for monitoring early-life growth trajectories in lambs at foot during lactation.

Chapter 6 examined factors associated with lamb survival using a database of 1210 lambs born to Poll Dorset ewes monitored using WOW technology from late gestation until weaning. Birth weight was the strongest predictor ($P < 0.001$) of lamb survival, showing a quadratic relationship because the lightest and heaviest lambs showed lower probability of survival. Lambing ease ($P < 0.001$) and litter size ($P < 0.05$) also affected survival. Integration of WOW-derived ewe pre-lambing LW revealed a quadratic effect ($P = 0.037$), with reduced survival in heavier ewes carrying heavier lambs. This thesis demonstrated the potential of WOW as a scalable tool for improving reproductive management and lamb survival in grazing sheep systems.

Chapter 1

Literature Review

1.1 Introduction

Australia's sheep industry represents a cornerstone of national agricultural production, with a long-standing history of contributing to both domestic food supply and global wool and sheep meat export markets. In 2024, Australia's national flock size was approximately 79.1 million sheep (Meat and Livestock Australia, 2024). In contemporary sheep production systems, reproductive efficiency is central to sustaining productivity, economic returns, genetic advancement, and enterprise resilience, as it directly determines weaning rates and overall biological performance (Martin et al., 2024). The reorientation of Australia's sheep industry toward meat-focused production has reshaped breeding decisions at the enterprise level, with many wool-based operations incorporating dual-purpose or terminal sires, such as Poll Dorset, to capture both meat and wool value. The interaction between producer management decisions and the physiological function of the pregnant ewe plays a pivotal role in determining lamb survival (Everett-Hincks & Dodds, 2008). Suboptimal survival rates prior to weaning represent a major constraint to reproductive efficiency and overall productivity in Australian sheep flocks (Brien et al., 2014).

The transition in sheep production systems from wool to meat has heightened producer interest in monitoring growth rates in ewes and lambs. Earlier research demonstrates that lamb liveweight (LW) and average daily weight gain (ADG) can differ throughout development (Leymaster & Jenkins, 1993; Djemali et al., 1994; Leeds et al., 2012). This shift reflects the increasing economic importance of optimizing growth efficiency to meet market demand and enhance enterprise profitability. New precision livestock farming (PLF) systems, such as automated walk-over-weighing (WOW), may enable the continuous, remote measurement of key performance indicators, including LW and ADG, under commercial grazing conditions to lift overall sheep production systems.

1.2 Sheep and Wool Industry

In Australia, sheep are predominantly managed within extensive, pasture-based systems where environmental variability plays a central role in shaping production outcomes (Harper et al., 2019). The interaction between seasonal rainfall, ambient temperature, and breed-specific reproductive physiology provides an opportunity for producers to strategically align mating and lambing with periods of peak forage availability, thereby improving ewe nutrition and lamb survival (White & Hastings, 2020). In this context, reproductive technologies such as artificial insemination (AI) may provide additional opportunities to enhance flock productivity. AI allows precise control over the timing of conception and facilitates the use of genetically superior sires, thereby accelerating genetic progress while supporting the synchronisation of lambing with periods of optimal feed supply (Evans & Maxwell, 1987). When integrated with strategic nutritional and health management, AI programs have been shown to mitigate the constraints of seasonal variability and improve reproductive efficiency, lamb survival, and overall enterprise profitability (Emsen.2025). Seasonality remains a defining characteristic of Australian sheep production systems, particularly across major breeding regions such as southern, western, and parts of eastern Australia. Distinct climatic patterns in these regions regulate pasture growth cycles and correspond closely with the natural breeding behaviours of Merino and prime lamb breeds (Harle et al., 2007).

To better understand and categorise this diversity, Hassall & Associates Pty Ltd (n.d.) developed for Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) a stratification model that defines five primary sheep production systems. Australia's sheep production systems can be broadly categorised into five primary flock types, each adapted to specific regional, market, and environmental contexts. These are: (1) Self-Replacing Wool flocks, (2) Self-Replacing Meat flocks, (3) Wether flocks, (4) Crossbred flocks, and (5) Traders and Others, which includes commercial feed lotting and non-traditional enterprises (Table 2.1).

Self-Replacing Wool flocks have traditionally formed the backbone of the sheep industry, especially in regions such as Western New South Wales, Western Victoria, and Western Australia's wheatbelt. These systems are based on Merino sheep, known for their superior wool quality. Self-replacing wool flocks breed their ewe replacements, with limited external purchases (primarily rams), making them largely self-sustaining. While historically wool focused, these flocks have increasingly diversified into meat markets by selling surplus young wethers and cast-for-age sheep. This shift has prompted dual-purpose breeding goals and greater emphasis on growth, fertility, and carcass traits alongside fleece quality.

Self-Replacing Meat flocks operate predominantly in higher rainfall or mixed farming areas, focusing primarily on meat production. These flocks derive more than half their income from sheep and lamb sales and commonly use breeds such as Poll Dorset and non-wool types like Dorper and Australian White. Terminal sire strategies are widely used, mating older or lower-performing ewes to produce fast-finishing 1st cross lambs with desirable carcass traits.

Wether flocks, while less common, are important in pastoral regions where reproduction and lamb finishing can be limited by poor land quality and increase risk of predation due to larger paddock sizes. These flocks consist largely of castrated males retained for wool production over multiple shearing cycles. As there is no internal breeding, wethers are periodically purchased. Though less efficient, these systems persist where wool remains viable and other land uses are restricted (i.e. cropping).

Crossbred flocks combine Merino or Merino cross ewes with terminal sires to maximise both maternal and carcass traits. Common in southern Australia and higher rainfall locations, these systems focus on producing prime lambs and typically outsource maternal replacements, aligning with high growth, market driven supply chains.

Traders and other flocks include short term trading enterprises and feedlots that finish lambs for rapid resale. Though not breeding focused, these systems enhance market flexibility and ensure continuity of lamb supply, particularly under climate variability or feed shortages.

Understanding the structure and function of the five primary production systems is essential for evaluating the economic and biological sustainability of the national flock. These systems not only reflect different production objectives but also represent adaptive strategies in response to shifting commodity markets and climate conditions. Future developments in reproduction, genetics, pasture management, and precision livestock technologies are likely to further influence the distribution and performance of these systems across Australia.

Table 2. 1 Australian sheep flock production systems and their descriptions

Production System	Description
Self-replacing Wool Flock	Flocks breed their own ewe replacements and sell surplus sheep, with a focus on wool production.
Self-replacing Meat Flock	Flocks that focus on meat production, with more than 50% of receipts from sheep and lamb sales.
Wether Flock	Flocks where more than 50% of sheep are wethers, with replacement wethers purchased and surplus sold.
Crossbred Flock	Flocks with crossbred ewes, selling all young sheep as lambs, often with first-cross ewes mated to meat rams.
Traders and Others	A category for sheep not classified in other sectors, including feedlots.

1.3 Importance of Reproduction in Sheep Production

The reproductive success of a flock is typically measured through parameters such as conception rates, lambing percentages and pre-weaning survival (Davies, 2019; Shorten et al., 2020).

Reproductive inefficiencies, such as barren ewes, perinatal mortality or mismothering, can lead to

significant production losses and reduced farm profitability (Hinch & Brien., 2013). Reproductive performance, therefore, is a central pillar of productivity and sustainability in sheep production systems (Simões et al., 2021), influencing both short-term outputs and long-term genetic advancement. At its core, reproduction governs the number of lambs born and subsequently weaned (Kenyon et al., 2014). Refshauge et al, (2024) determined that in Australia ewe pregnancy rates were highest in the wheat sheep and high rainfall zones (both averaging 0.76), compared to 0.72 in the pastoral zone. Reproduction rates followed similar trends, with wheat-sheep and high rainfall zones averaging over 1.2 lambs per ewe, versus 1.1 in pastoral systems.

Reproductive success can be evaluated various ways including measuring the number of lambs born and weaned, and number of conceptions that fail to progress to parturition, as well as ewe losses during gestation and lactation (Jainudeen & Hafez, 2000). Recorded reproductive wastage in ewes encompasses multiple stages, from failed conception, embryonic loss, stillbirth, and neonatal death (Jainudeen & Hafez, 2000). In the context of livestock systems, every behavioural choice an animal makes has consequences that shape its future performance (Harrison et al., 2011). How and when an animal acquires energy or nutrients, and how those resources are distributed between maintenance, growth, and reproduction, can determine its reproductive success, longevity, and genetic contribution to future generations (Harrison et al., 2011).

Lamb mortality is a critical issue in sheep production systems worldwide, with both welfare and economic implications. In New Zealand, mortality rates from birth to weaning typically range between 15% and 25%, influenced by farming systems and prevailing climatic conditions (Kenyon et al., 2014b; Morris, 2017). On average, lamb mortality rates of around 10% for single-born lambs and up to 30% for twin-born lambs are considered common. Earlier research by Wilkins and Croker (1990) found that early pregnancy losses accounted (< day 20) was estimated at 10-15% of single and 10-25% of twin ovulation. Hinch and Brien (2014) found in Australia on average, between 20% and 30% of lambs fail to survive weaning with

approximately 74% of deaths occurring within the first three days of life. This concentration of death early in the lamb's life cycle underscores the critical importance of the perinatal window, where factors such as birthweight, ewe nutrition, maternal behaviour, lamb vigour, and climatic exposure interact to determine survival outcomes. Sheep producers in extensive grazing systems often underestimate the scale of reproductive losses, including embryonic mortality and lamb deaths relative to the number conceived (Kopp et al., 2019). Consequently, they have a limited understanding of the substantial reductions in profitability caused by reproductive wastage (Young et al., 2011; Kopp et al., 2019).

Bunter et al., (2023) though noted that lamb survival is a lowly heritable trait influenced by both direct genetic and maternal effects. While individual lamb survival is positively associated with birth weight, it is negatively correlated with gestation length, lambing ease score (i.e., increasing difficulty), and the incidence of dead-at-birth (DAB) lambs (Bunter et al., 2023). Moderate genetic positive correlations were found between DAB lambs and lambing ease (0.40 to 0.45 for singles; 0.15 to 0.36 when twins are included), while strong negative correlations were observed between dead-at-birth and lamb survival (-0.63 to -0.81 for singles; -0.00 to -0.23 including twins) (Bunter et al., 2023). Lamb survival is a complex trait influenced by both direct genetic effects (e.g., lamb viability, birthweight) and maternal genetic effects (e.g., uterine environment, mothering ability), as well as a wide range of non-genetic factors (nutrition, weather, management) (Brien et al., 2014; Everett-Hincks et al., 2014; Bunter et al., 2023).

Additionally, effective reproduction underpins flock resilience by supporting a stable supply of replacements and offering flexibility in responding to environmental or market challenges (McHugh et al., 2022). To assist Australian sheep producers, Australian Sheep Breeding Values (ASBVs) have been developed to accelerated genetic gain to support more precise selection decision (Mortimer et al., 2023). ASBV genomic testing has allowed producers to select breeding animals with superior traits (MLA, 2023). This is particularly vital in structured breeding programs, such as those focused

on maternal traits, like fertility, lamb survival, and mothering ability, or terminal sire traits, including growth rate, carcass yield, and meat quality (McHugh et al., 2022).

Nutritionally, producers that have ewes in poor body condition in late gestation has been associated with increased incidence of stillbirth, low birth weight, hypothermia in lambs, and elevated ewe mortality due to metabolic disorders such as pregnancy toxemia (Hinch & Brien, 2014). Conversely, over conditioned ewes may experience increased risk of dystocia and compromised lactational performance, particularly in extensive grazing systems where sudden energy demands postpartum are not always matched by forage availability (Jacobson et al., 2023). Post-weaning and adult sheep mortalities are also problematic, with large-scale, extensive grazing enterprises exposed to nutritional limitations and harsh environments contributing to high seasonal losses (Hatcher et al., 2009). Thus, regular and strategic BCS monitoring facilitates timely nutritional interventions may mitigate these risks and improve both reproductive performance and welfare outcomes.

One key practical tool used by producers for arresting poor survival of ewes and lambs is the use of body condition score (BCS). Understanding how to manage ewes within optimal BCS ranges has continued to become fundamental in improving reproductive outcomes. A survey conducted by Bates et al. (2023) involving 52 sheep producers revealed that 81% used BCS, with 90% of them employing the standardised five-point scale. Furthermore, 71% of participants reported applying BCS specifically at joining time to assess and optimise the nutritional status of ewes.

BCS is a critical management tool in sheep production systems, providing a tactile, qualitative assessment of fat and muscle reserves. Unlike liveweight (LW), which offers a quantitative measure of mass, BCS evaluates an animal's energy balance, allowing for targeted nutritional and reproductive interventions throughout the production cycle (Jefferies, 1961; Walkom & Brown, 2016; Haslin et al., 2023). The standardised BCS system operates on a scale from 1 (emaciated) to 5 (obese), with increments of 0.5 or even 0.25 allowing for refined assessment

(Jefferies, 1961). Scoring is based on manual palpation of the lumbar spine and short ribs, anatomical regions where subcutaneous fat and muscle reserves are most responsive to nutritional status (Semakula et al., 2020). According to the Lifetime Wool Guidelines, an average BCS of 3.0 at mating is recommended to maximise ovulation and conception rates, while a minimum score of 2.5 should be maintained throughout gestation to support foetal development and ewe health (Refshauge et al., 2023). Vialoux (2020) reported that pre-mating BCS in the range of 3.0 to 3.5 is positively correlated with ovulation rate and successful conception. Furthermore, Van Burgel et al. (2011) demonstrate that late pregnancy BCS targets should differ based on litter size: a BCS of 2.7 for single-bearing ewes and 3.3 for twin-bearing ewes supports better maternal care and improved neonatal survival. Particularly during energy-demanding periods such as late gestation and early lactation, BCS provides a real-time, animal-level indicator that complements flock-level LW data (Van Burgel et al., 2011; Refshauge et al., 2024). Furthermore, regular BCS monitoring across the production cycle allows producers to make proactive nutritional adjustments tailored to each stage, mating, gestation, lambing, and lactation, thereby reducing reproductive inefficiencies and enhancing ewe longevity (Young et al., 2011; Refshauge et al., 2023).

Continued emphasis on improving reproductive efficiency through integrated management and scientific innovation will be essential for ensuring the long-term viability and competitiveness of the Australian sheep industry. Future research should continue to address the complex genetic and environmental interactions that shape reproductive performance in sheep. The capacity of ewes to conceive, maintain pregnancy, and rear lambs to weaning fundamentally determines the number of saleable animals produced for meat and wool enterprises each year. Advancing reproductive efficiency not only supports genetic progress but also enhances resource-use efficiency and strengthens enterprise resilience under variable market and climatic conditions.

Priority areas for investigation in reproduction for sheep include deeper exploration of maternal efficiency traits, improved understanding of foetal development, and the integration of precision livestock technologies capable of delivering real-time reproductive and BCS insights. At the same time, reproductive strategies must be aligned with broader industry goals relating to animal welfare, environmental sustainability, and climate adaptation. Conversely, existing priorities include reducing lamb mortality, enhancing reproductive rates, and improving feed conversion efficiency under variable climatic conditions (MLA, 2023). New and developing PLF technologies are playing a growing role in reproductive management (Gonzalez et al., 2011; Gonzalez-Garcia et al., 2018; Leroux et al., 2023). Real-time data generated by automated monitoring systems provides producers with the capacity to refine critical management decisions, including mating schedules, lambing strategies, and weaning practices (Emsen et al., 2025). As these technologies become increasingly integrated, the Australian sheep industry is well-positioned to leverage ongoing investment in digital agriculture and value-chain integration, supporting both productivity and sustainability into the future.

1.3.1 Nutrition

The growth and development of meat animals, including sheep, are influenced by a complex interplay between genetic and non-genetic factors, both of which contribute to variation in LW and ADG (Alemneh & Getabalew, 2019). Livestock production systems are increasingly vulnerable to unpredictable climate variability, which directly affects pasture growth and forage availability (Seo et al., 2010). Variability in rainfall, temperature extremes, and seasonal shifts alter the timing and duration of plant growth cycles, often leading to mismatches between feed supply and animal nutritional requirements (Morris, 2017). Extended droughts, unseasonal rainfall, or reduced pasture productivity can compromise both the quantity and quality of forage, resulting in feed shortages that affect liveweight gain, reproductive efficiency, and overall flock health. Ewe nutrition during gestation is a critical determinant of reproductive success and lamb viability in sheep production systems (Ferguson et al., 2011; Rassa et al.,

2004). Therefore, nutrition plays a central role in LW, as the balance of energy, protein, and minerals directly affects tissue accretion, metabolic efficiency, and average daily growth patterns (Black, 1988; Owens et al., 1995)

Inadequate maternal nutrition during gestation can reduce birthweight, compromise neonatal thermoregulation, and lower survival chances for lambs (Thompson et al., 2011). Similarly, ewes in suboptimal BCS at lambing often produce insufficient colostrum and milk, increasing lamb susceptibility to hypothermia and starvation (Kenyon et al., 2014b). Energy protein imbalances in late pregnancy are particularly detrimental, as they can reduce lamb vigour and impair ewe maternal behaviour, both of which are critical during the early bonding period (Everett-Hincks & Dodds, 2008). However, Curnow et al. (2011) results have shown that strategic liveweight gain during mid-gestation, followed by stabilisation of condition in late gestation, is linked with increased placental efficiency and better lamb survival outcomes. This strategy may ensure that the ewe's energy reserves are sufficient without leading to over-conditioned animals, which may also present complications at lambing, such as increased risk of dystocia. The timing of supplementation feeding is critical; interventions too late in gestation may not provide sufficient time to reverse the effects of undernutrition on foetal development or milk production. Supplementation strategies trialled in various Australian rainfall zones have yielded differing results, underscoring the importance of tailoring approaches to local conditions (Meat and Livestock Australia [MLA], 2017). In higher rainfall regions, for example, pastures may be adequate during early gestation but decline in quality during late pregnancy, necessitating energy and protein supplementation. In contrast, in low rainfall or drought-prone areas, more consistent feed supplementation across gestation may be necessary.

However, the type of supplement also matters. Energy dense feeds such as cereal grains can boost ewe condition quickly but must be introduced gradually to avoid ruminal acidosis. Protein sources, such as lupins or canola meal, are especially valuable in supporting foetal growth and

colostrum production (Masters & Mata., 1996). Therefore, targeted nutritional strategies and consistent monitoring of body condition score and LW throughout gestation are essential to achieving optimal reproductive and welfare outcomes (Haslin et al., 2023). Feed intake and feed nutritional quality are key factors affecting animal growth, along with animal species, sex, and age (Li et al., 2024).

Animal growth is defined as the progressive increase in tissue mass resulting from the accumulation of protein, fat, and bone (Moloney & McGee, 2023). This process reflects structural and developmental changes across organs and tissues (Black, 1988; Owens et al., 1995). Daily weight gain or loss reflects the efficiency of feed digestion and absorption by the animal. Liveweight in livestock can fluctuate rapidly without changes in body energy reserves, primarily due to varying amounts of food and water in the gastrointestinal tract (Moloney & McGee, 2023).

Animal production efficiency (as determined via measuring ADG) can be compromised when livestock graze single species pastures due to the presence of anti-nutritional compounds such as nitrates or glucosinolates in brassicas (Barry, 2013) or imbalances in energy, protein, and minerals, such as sodium or magnesium deficiencies in cereal crops (Masters, 2016). Mixed-species forage systems may reduce these risks by providing animals with greater dietary choice, enabling them to select a more balanced intake (Provenza & Balph, 1990). Clayton et al. (2024) noted ewe lambs grazing forage mixtures including brassica generally had higher ADG than those grazing brassica alone, likely due to greater dry matter (DM) and energy intake. It was noted further in (Clayton et al., 2024) that lambs grazing a forage mixture of brassica, clover and lucerne gained more LW between Days 21 and 35 compared with those on simpler mixes, suggesting later-stage advantages in intake or more stable growth. Although overall weight gain did not differ among treatments, female lambs grazing brassica alone showed lower ADG in the

first 21 days, possibly reflecting sex-based differences in energy use or metabolism (Clayton et al., 2024).

Finally, ewe nutrition during gestation is a cornerstone of reproductive success and lamb survival in the Australian sheep industry. Maintaining optimal BCS and LW through targeted nutritional interventions enhances foetal development, improves lamb birth weight, supports lactation, and promotes positive maternal behaviour. The timing, type, and location-specific tailoring of supplementation are all critical to achieving these outcomes. As the industry faces increasing challenges from climate variability and sustainability pressures, investing in improved nutritional management, supported by data driven technologies and ongoing research, remains a key pathway to improving flock productivity and animal welfare.

1.4 Precision Livestock Monitoring in Sheep

Precision Agriculture (PA) originated in cropping to improve resource-use efficiency through spatial and temporal variability in management (Gebbers & Adamchuk, 2010). Its extension into livestock has led to Precision Livestock Farming (PLF), which emphasises continuous, automated, often real-time monitoring of individual animals to enhance decision-making, productivity, welfare, and sustainability (Berckmans, 2017). In extensive Australian sheep enterprises, PLF provides practical means to improve reproductive outcomes, optimise feed allocation, and detect early indicators of health and welfare issues, thereby reducing preventable losses (Khan et al., 2025). Aligning with economic and environmental objectives, precision livestock monitoring represents a credible pathway to innovation and resilience (Gebbers & Adamchuk, 2010; Berckmans, 2017).

1.4.1 Defining Precision Livestock Monitoring

Precision agriculture is a management strategy that gathers, processes, and analyses temporal, spatial, and individual data to support management decisions for improved productivity, profitability, and sustainability (Precision Agriculture, 2025). Translated into livestock contexts, PLF

integrates real-time sensor data with computational models to capture dynamic changes in animal physiology and behaviour (Tullo et al., 2019).

PLF systems generally involve four functional components:

1. Sensors — to capture individual animal identification and physiological measures (e.g., LW, temperature and feeding behaviour).
2. Data processing models — to process raw data within the context of biological processes.
3. Targets and trajectories — to define expected patterns of growth, reproduction, or productivity.
4. Feedback mechanisms — to enable adaptive management, such as feed allocation or health interventions (Gonzalez et al., 2011; Gonzalez-Garcia et al., 2018).

Globally, PLF research has accelerated in dairy, beef, and swine systems, where sensors are routinely applied for oestrus detection, rumination monitoring, or automated weighing (Caja et al., 2016). PLF tools enable continuous, minimally invasive monitoring of behaviour, physiology, and nutrition, providing near real-time data streams that can inform management decisions at both the flock and individual-animal level. However, sheep production has historically been slower to embrace digital technologies, constrained by the extensive scale of enterprises, infrastructure challenges, and comparatively lower economic margins per animal. Traditional management practices such as yard-based weighing, pregnancy scanning, and body condition scoring (Jefferies, 1961), while foundational, are inherently labour-intensive, stressful for animals, and restricted to infrequent snapshots of performance (Rutten et al., 2013). Importantly, PLF addresses the limitations of traditional methods by capturing dynamic changes in animal condition across critical periods such as gestation, lactation, and recovery. Recent developments in hardware and associated digital platforms are beginning to overcome these barriers by providing minimally invasive monitoring tools that integrate with existing management practices (Khan et al., 2025). These innovations should not

only reduce labour demands but also generate continuous streams of actionable data, positioning WOW technologies as a transformative step toward precision management in extensive sheep enterprises (Gonzalez-Garcia et al., 2018).

1.4.2 WOW Technologies

Internationally, WOW and comparable systems have been validated across multiple livestock species. In dairy cattle, automated weighing has demonstrated accuracy in tracking milk production efficiency and nutritional responses (Alawneh et al., 2011). Similarly, in dairy ewes, WOW systems have been employed to monitor lactational performance under commercial conditions, demonstrating their capacity to detect short-term changes in bodyweight associated with milk yield and energy balance (Hassoun et al., 2021). Within sheep meat enterprises, validation studies in both Australia and Europe confirm that WOW provides reliable estimates of LW trajectories and can differentiate between single- and multiple-bearing ewes (Brown et al., 2013; González-García et al., 2018). Collectively, these findings indicate the increasing maturity of WOW as a practical, industry-relevant PLF tool. By generating continuous LW data under commercial grazing conditions, WOW may facilitate a shift away from the static and retrospective insights provided by conventional methods. Its capacity to identify subtle shifts in ewe LW across reproductive stages may create opportunities for earlier, more targeted interventions to reduce reproductive inefficiencies and improve lamb survival. However, there is limited research demonstrating these capabilities of WOW in supporting sustainable intensification via enhancing productivity while reducing labour, improving animal welfare, and contributing to environmental goals.

WOW systems comprise platforms mounted on load cells and integrated with electronic identification (EID) technology. These systems automatically record LW when animals voluntarily cross the platform, typically enroute to water or supplementary feed. Each crossing generates a timestamped bodyweight measurement that is directly linked to the animal's unique identity through radio-frequency identification (RFID) (Wishart et al., 2017; Bates et al., 2023). Data is stored

locally or transmitted via Wi-Fi, Bluetooth, or mobile networks (González-García et al., 2018).

Increasingly, wireless sensor networks (WSNs) are being deployed to integrate WOW outputs with environmental and behavioural information, enabling more holistic monitoring of grazing systems (González et al., 2014). The data richness of these systems is considerable; WOW units can generate tens of thousands of records within a single trial. For example, Alawneh et al (2011) collected 79,697 records from 463 dairy cows, reporting strong concordance with static weights. Similarly, González-García et al (2018) obtained thousands of voluntary crossings from sheep under both intensive and extensive grazing conditions. Thompson et al (2013) confirmed that as flock size increased, data density decreased unless multiple WOW units were deployed, or sampling time windows extended. Brown et al (2013) reported that five-day sampling intervals produced flock average LW estimates within ± 2 kg at 95% confidence, while one-day intervals were less accurate. Larger flocks are also more prone to dominance effects, where socially dominant individuals monopolise access to attractants (Hong et al., 2017).

The continuous nature of WOW data may enable producers to monitor LW trajectories with high temporal resolution, enabling them to detect deviations from expected growth patterns at an early stage. However, the effectiveness of WOW however depends largely on the targeted animals' willingness to pass through the system. Common attractants include water, supplementary feed, mineral licks, and shade (Brown et al., 2013; Wishart et al., 2017). Water is the most consistent attractant, particularly in dry conditions where access is limited to one or two points per paddock. In Merino trials (results not published), it was observed that positioning a WOW unit with water as the sole attractant in grazing paddocks was ineffective, as rainfall accumulated in ground depressions, reducing the sheep's need to visit dams or troughs for drinking. Thus, positioning a WOW platform at the sole water source ensures frequent crossings but biases data toward peak watering times. Feed (grain feeders / hay) and mineral licks can increase passage rates, especially in systems with multiple water points, but may alter natural grazing behaviour or nutritional balance (González-

García et al., 2018). Shade can also encourage passage during hot conditions, though its effectiveness varies seasonally.

WOW systems as they advance with new technologies may fundamentally change the paradigm of monitoring of health and welfare change in an animal by providing continuous, automated monitoring of LW at the individual animal level. This high temporal resolution may make it possible to detect subtle deviations in LW that may be imperceptible using conventional tools (Brown et al., 2012; González et al., 2014). Importantly, WOW data may reveal complex and non-linear associations between LW patterns, environmental factors, and reproductive outcomes using advanced computational and statistical methods such as machine learning and time-series modelling (Thorup et al., 2020; Pal et al., 2023).

The WOW systems are among the most mature PLM technologies and have been validated in a range of sheep production contexts. Studies have shown that WOW platforms capture accurate and repeatable LW measurements that are strongly correlated with conventional yard-based LW (Brown et al., 2012; Brown et al., 2013). A critical advantage of the WOW is its capacity to collect LW without the need for manual handling, thereby reducing animal stress, minimising labour demands, and providing higher-frequency data compared to traditional methods (Bates et al., 2023). Advances in error decomposition, linear modelling, and calibration protocols have significantly improved the accuracy and reliability of WOW outputs (Brown et al., 2014; Gonzalez et al., 2014; Gonzalez-Garcia et al., 2018). These refinements can highlight the technological maturity of WOW relative to other PLF tools, positioning it as a cornerstone technology for precision sheep enterprises.

Beyond direct productivity benefits, WOW contributes to sustainability outcomes. By enabling more precise feed allocation, Hegarty et al (2021) demonstrated in northern Australian cattle that the application of remote technologies, such as WOW, can reduce supplement wastage and enhance nutrient-use efficiency. Comparable investigations have yet to be conducted in sheep under commercial production systems. Moreover, the continuous data streams generated by WOW

provide an invaluable research resource for developing predictive models of growth, reproduction, and health in sheep. For example, Pal et al (2023) demonstrated how WOW data can be used in dynamic modelling frameworks to forecast critical thresholds for weight loss or gain, supporting real time decision making under commercial conditions.

Not all records are usable: movement artefacts, incomplete crossings, or multiple animals on the platform often create spurious values. However, the high frequency of data ensures that enough valid records remain after filtering to support reliable flock- and individual-level analysis (Hassoun et al., 2013). Raw WOW data require extensive filtering. A common two-step process involves: (i) removing biologically implausible records (e.g., zero weights, double crossings), and (ii) removing potentially erroneous values outside an individual's expected range (Alawneh et al., 2011; González-García et al., 2018). The Australian Sheep CRC's WeighMatrix software incorporated historical data to refine accuracy (Brown et al., 2012). Analytical approaches range from simple averaging to spline smoothing and mixed-effects models. Brown et al. (2013) used five-day averages to achieve robust flock-level estimates. Hassoun et al (2021) validated WOW for lactating dairy ewes, confirming its ability to detect short-term changes in BW during lactation. In Poll Dorset ewes, spline-based analysis of WOW data revealed distinct LW trajectories for single- versus twin-bearing ewes, offering actionable insights for reproductive management. Moreover, the continuous data streams generated by WOW provide an invaluable research resource and practical applications for developing predictive models of growth, reproduction, and health in sheep.

1.4.3 Applications of PLM to Reproductive Management

In extensive grazing systems such as those common in Australia, managing reproduction is particularly challenging due to limited opportunities for close observation and the logistical constraints of monitoring large flocks across diverse and often remote landscapes (Martin et al., 2024). According to Swain et al. (2018) WOW systems also support reproductive management. Monitoring of LW dynamics in pregnant and lactating ewes may contribute to predictive modelling

of reproductive status and lambing timing. However, such predictions are based on statistical associations and do not establish causal mechanisms underlying observed changes in LW trajectories. Research has demonstrated that ewes with suboptimal LW trajectories are more likely to experience reproductive complications and lower lamb survival (Oldham et al., 2011; Refshaugue et al., 2015). Thompson et al. (2021) suggested that the WOW provides an evidence-based method of detecting such risks before they compromise flock performance. Subclinical disease often manifests as subtle deviations in liveweight gain or fluctuations in feeding behaviour. In addition to reproduction, WOW therefore can play a pivotal role in monitoring animal health and welfare via remotely monitored LW assessment (Leroux et al., 2023). By integrating WOW with EID, producers can attribute LW data to individual animals, enabling the identification of health problems at the ewe level rather than at the flock level. This detailed monitoring is particularly valuable in extensive systems where visual inspection is infrequent, and the autonomous operation of walk-over weighing (WOW) makes it especially suited to remote, labour-constrained enterprises where regular yard weighing is impractical (Wishart et al., 2017).

1.4.4 Application of WOW in Extensive Production Systems

Bunter et al. (2023) demonstrated that ewes with stable or moderate weight loss during lactation tended to have higher lamb survival rates, whereas those exhibiting sharp declines were more likely to experience losses. These findings highlight the potential of WOW data to serve as an early-warning system, signalling the need for targeted interventions to reduce mortality. Over time, such models can be refined to generate predictive algorithms that identify lambs at risk based on maternal weight patterns, enabling pro-active action (Gonzalez-Garcia et al., 2018).

Monitoring lactational performance via WOW also has broader implications for ewe welfare and longevity within the flock. Ewes that experience repeated episodes of nutritional stress during lactation are more likely to suffer from reduced reproductive capacity in subsequent seasons, lower overall productivity, and increased culling rates. Continuous LW monitoring allows producers to

track the cumulative impacts of lactation across multiple reproductive cycles, thereby informing decisions about ewe retention, culling, and replacement (González-García et al., 2021). From a welfare perspective, the ability to detect and address nutritional challenges early reduces the incidence of prolonged suffering associated with undernutrition or disease. Beyond its immediate on-farm applications, the collection of continuous post-partum LW data via WOW contributes to the scientific understanding of lactational physiology and its relationship with lamb outcomes. By providing large, high-frequency datasets under commercial grazing conditions, WOW enables researchers to test hypotheses that were previously restricted to controlled experimental settings. These insights can then be translated into practical management guidelines that improve reproductive efficiency and lamb survival across diverse production systems. For industry, this capacity to generate evidence-based recommendations strengthens extension services and supports adoption by demonstrating clear links between technology use and productivity gains.

1.4.5 Post-Partum Nutrition, Lactational Performance, and the Role of Walk-Over-Weighing

The post-partum period is universally recognised as a critical stage in sheep production (Menzies, 2007), during which maternal nutrition and lactational performance exert direct and profound effects on lamb survival, growth trajectories, and overall enterprise productivity (Gardiner et al., 2007). PLF technologies, particularly WOW systems, provide an unprecedented opportunity to monitor these processes continuously, enabling early detection of nutritional deficits and supporting interventions that improve both ewe and lamb outcomes (Brown et al., 2012; Gonzalez-Garcia et al., 2018; Leroux et al., 2023). The capacity of WOW systems to capture high frequency LW data may provide opportunities for livestock managers to distinguish between expected and pathological weight changes. It has been suggested that establishing baseline LW trajectories for lactating ewes using WOW may assist in identifying individuals deviating from expected patterns (Brown et al., 2013). However, such deviations represent statistical departures from baseline trajectories and do

not, in themselves, establish causality or confirm that subsequent production or survival outcomes are directly attributable to the observed LW changes. This targeted approach not only supports maternal recovery but also improves the survival and growth of dependent lambs. Importantly, such interventions reduce the inefficiencies associated with blanket supplementation strategies, in which feed is provided uniformly to entire flocks regardless of individual need.

Aligned with Brown et al. (2013), WOW-derived baseline trajectories enable early detection of ewes departing from optimal LW and ADG patterns. Building on this framework, this thesis aimed to develop individual animal trajectory models and practical deviation criteria to prioritise animal specific LW and ADG changes over time for ewes and lambs. This targeted approach provides evidence for future research into ewe maternal recovery, improvement into lamb survival and growth, and may be used to assess animal dietary intake via supplementary feeding stations located within the WOW confinements.

1.5 Research Gaps and Future Directions

Despite growing interest in PLF and increasing validation of WOW technologies in research settings, several important gaps remain in the literature. These gaps limit the ability of the technology to be applied confidently and consistently in commercial sheep enterprises, particularly within extensive Australian systems. Addressing these gaps will be essential to fully realise the benefits of WOW in improving reproductive efficiency, lamb survival, animal welfare, and sustainability outcomes.

Most validation of WOW has been undertaken in controlled or semi-intensive environments (Brown et al., 2012; González-García et al., 2018; Hassoun et al., 2021). While these studies confirm the accuracy and repeatability of WOW data compared with yard-based weighing, there remains limited evidence under the extensive conditions that typify Australian sheep production. Larger paddock sizes, multiple water points, variable infrastructure, and environmental stressors all affect animal behaviour and therefore data quality. Furthermore, there is a lack of long-term studies that evaluate WOW performance across multiple seasons, years, and reproductive cycles. Issues such as sensor

durability, maintenance requirements, and data reliability over extended periods remain largely untested. Without these validations, it is difficult for producers to fully trust the system's consistency in commercial contexts.

Multisite, multiyear trials are required across diverse Australian environments to validate WOW performance, reliability, and data accuracy under commercial grazing conditions. This thesis provides new research focus on refining predictive algorithms for reproductive management by incorporating multi-source datasets, including behavioural and physiological sensor data alongside WOW-derived LW (Thorup et al., 2020; González et al., 2014). It will also investigate the potential for adaptive algorithms that can recalibrate predictions in real time as new data are collected, thereby providing continuously updated forecasts of reproductive outcomes (Bates et al., 2023; Pal et al., 2023). Future research can then provide longitudinal studies under commercial grazing conditions to validate predictive models across seasons, breeds, and regions, thereby improving their generalisability (Bunter et al., 2023).

Environmental conditions are well established as major drivers of sheep reproduction and productivity (Glasgow et al., 2004; Ferguson et al., 2020), yet few studies have combined WOW data with environmental variables. Most analyses continue to assess LW trajectories in isolation, overlooking the influence of factors such as heat stress, drought, pasture availability, and management interventions. This narrow focus reduces interpretive value, since weight loss during late gestation, for instance, may stem from feed scarcity rather than intrinsic reproductive failure. Integrating WOW datasets with climate records, pasture biomass, and water quality measures would improve the ability to distinguish between physiological and environmental effects. Further progress also depends on developing algorithms that link LW dynamics to reproductive outcomes, health events, and welfare indicators, thereby translating raw data into actionable insights. Combining WOW outputs with complementary tools such as accelerometers and global navigation satellite systems (GNSS) may create a more holistic picture of animal performance. Equally important, the

success of these systems relies on user-friendly platforms and decision-support dashboards that can present complex datasets in ways that are accessible, practical, and directly useful for producers. Development of integrative modelling frameworks that combine WOW with remote sensing, climate, and pasture datasets to generate holistic insights into reproductive efficiency. Technical validation alone is insufficient to guarantee adoption.

Cost reduction and scalability, and a quantification of productivity and economic gains as a result of using the technology remain critical considerations for the broader adoption of WOW technology in sheep enterprises. The development of modular, solar powered platforms as developed in the present thesis has the potential to lower infrastructure costs, improve accessibility for small producers, and facilitate deployment in remote regions where energy supply and labour availability are constrained. Equally important are collaborative industry initiatives that provide training, extension support, and participatory research opportunities. Such efforts are essential for building producer confidence, demonstrating value in practical settings, and encouraging uptake across diverse production systems. As a PLF tool, WOW represents a transformative opportunity for the Australian sheep industry.

Beyond attractant use, animal behaviour introduces additional complexity into the representativeness of WOW datasets. Social hierarchies can influence access, with dominant individuals more likely to monopolise resources near the weighing platform, while shy or subordinate animals may avoid crossing altogether. These behavioural dynamics may skew data collection, leading to systematic under-representation of particular groups within a flock. Variation in passage rates has also been observed across breeds, flock sizes, and production environments, but these dimensions remain poorly quantified. As a result, the behavioural aspects of WOW operation remain one of the least explored yet most influential factors affecting data reliability and interpretation.

These behavioural considerations are particularly important when WOW is applied to reproductive and health monitoring. Several studies have demonstrated associations between LW trajectories and reproductive outcomes, including conception rates, lamb survival, and ewe longevity (Oldham et al., 2011; Bunter et al., 2023). However, the causal mechanisms underpinning these associations are not yet fully understood. For instance, while declining LW during late gestation may correlate with increased neonatal mortality, it is unclear whether this reflects insufficient maternal nutrition, foetal growth restriction, or an interaction of environmental and physiological stressors. Similarly, although WOW has the potential to detect deviations linked to subclinical disease or maternal stress (Leroux et al., 2023), these applications remain speculative and require formal validation.

At present, this limits the role of WOW to that of a monitoring platform rather than a diagnostic tool. Producers are provided with high frequency LW data but lack robust frameworks to interpret these signals as early warnings of reproductive risk or disease burden. For commercial adoption, the ability to identify and intervene before losses occur is critical. Unlocking this potential will depend on research that integrates behavioural science, nutritional physiology, and reproductive biology into the design and application of WOW systems.

Future research should quantify the influence of type of attractant (e.g. water, salt, molasses, pellets), flock size, breed differences, and social hierarchies on WOW usage and data representativeness. In addition, the development of predictive models, the integration of WOW with other PLF tools, and accessibility for diverse enterprise scales should also be investigated. Despite these benefits, adoption remains constrained by technical challenges, economic barriers, and producer scepticism. If successfully implemented, WOW could not only transform sheep management but also set a benchmark for the broader adoption of precision monitoring technologies across the livestock industries.

1.6 Summary

The present literature review concludes that the integration of WOW technology with advanced predictive analytics could present a transformative advance for sheep production. The WOW technology could convert LW records into actionable insights, which may enable earlier, more precise interventions that improve productivity, lamb survival, and sheep welfare, and reduce environmental impacts (Brown et al., 2013; González et al., 2014). However, there is not sufficient scientific information demonstrating such potential and further research with the WOW technology for sheep production is recommended, specially under commercial conditions. To understand the potential of the WOW technology, future research should focus on ewes and lambs LW monitoring across the reproductive states (gestation and lactation) until weaning because these periods are of utmost importance for the productivity and welfare of sheep enterprises. Challenges of data quality, interoperability, and adoption remain, but these are surmountable through sustained investment in research, infrastructure, and extension. As the Australian sheep industry adapts to increasing climate variability and global sustainability pressures, technologies such as WOW exemplify the role of PLF in building resilience. By embedding predictive, data-driven reproductive management within commercial enterprises, the industry can achieve gains not only in productivity but also in welfare and environmental performance. The transition from reactive to proactive reproductive management could thus represent not just an incremental improvement but a redefinition of how sheep systems are managed in the twenty-first century.

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Chapter 2

Objectives and Hypothesis of this Thesis

The general objectives of the present thesis were to study the feasibility and potential of remote in-paddock automatic weighing of sheep using walk-over-weighing (WOW) technology in commercial grazing enterprises and to integrate such data with pregnancy and lambing data.

2.1 General hypothesis of the thesis

The general hypothesis of this thesis proposed that WOW technologies can capture high frequency LW data and such data is associated with key productivity and welfare outcomes in sheep, such as lamb survival, reproductive efficiency, and growth trajectories in pregnant and lactating ewes and their lambs.

2.2 Objectives of each chapter

To address these general aims and hypothesis, the present thesis was designed with four chapters prepared for publication each with specific experimental objectives. The objectives of each chapter were as follows:

Chapter 3. To investigate the relationship between traditional YW and LW recorded by WOW systems using simple linear regression, mean and linear bias, error decomposition, and Lin's concordance correlation coefficient (LCCC).

Chapter 4. To investigate the differences in remotely collected LW and ADG in artificially inseminated (AI) ewes bearing single or twin foetuses.

Chapter 5. To evaluate differences in LW and ADG collected using WOW systems of lambs weaned from single, twin, or triplet litters in Poll Dorset lambs under commercial grazing conditions.

Chapter 6. To study factors affecting lamb survival including remotely collected ewe LW and ADG, lamb birth weight, gestation length, lambing ease, gender, maternal wool length, litter size.

Chapter 3

Precision and accuracy of remotely collected compared to traditional yard sheep liveweight

3.1 Abstract

This study validates the precision and reliability of walk-over weighing (WOW) systems relative to traditional yard weights (YW), establishing a foundational understanding of their correlation in sheep populations managed under extensive commercial grazing conditions. The study investigated the relationship between traditional YW as the dependent variable and weights recorded by a WOW as the independent variable using simple linear regression, mean and linear and random error, and Lin's concordance correlation coefficient (LCCC). The WOW weight was measured in paddock when animals entered a yard containing an attractant (water or minerals) and the YW using static scales placed in sheep yards. The dataset comprised of 5,786 paired observations. Linear regression yielded a strong coefficient of determination ($r^2=0.89$), but the slope (0.906 ± 0.0042) and intercept (1.32 ± 0.212) were different than the ideal 1 and 0, respectively ($P < 0.001$). The root mean square error (RMSE) was 7.73 kg, equivalent to 18.62% of observed YW, and a mean bias of -2.84 kg, indicating WOW weight slightly underestimation. Systematic bias contributed to 6.99% of the total error, whereas random error accounted for 81.95%, highlighting the inherent variability in sheep WOW data remotely collected in the paddock. This comprehensive analysis provided the foundation for understanding the relationship between YW and WOW in sheep populations under grazing conditions.

Key words: linear model, walk over weighing, yard weight.

3.2 Introduction

Monitoring liveweight (LW) in sheep using automated technologies such as WOW systems has emerged as a viable alternative to traditional weighing practices, offering advantages in data frequency, animal welfare, and labour efficiency (Wishart et al., 2017; Tzanidakis et al., 2023a;

Morgan-Davies et al., 2024). Collectively, these studies demonstrated that WOW systems and their derivatives—including mob-based platforms, multi-station devices, and remote telemetry integrated with individual electronic identification (EID)—offer accurate, reliable, and repeatable LW data collection across both controlled pen environments and extensive grazing systems.

Precision livestock farming (PLF) technologies such as WOW, significantly advance the capacity for continuous animal monitoring, enabling producers to make timely, data-driven decisions that improve animal welfare and production efficiency (Caja et al., 2020). Tzanidakis et al. (2023a) reported that despite the clear utility of PLF technologies, several technical and practical limitations persist, including financial barriers, complexity in use, and the limited availability of specialised support services. These constraints are compounded by data variability, challenges in equipment calibration, and environmental interference, which collectively hinder the reliability and scalability of such systems in commercial applications (Brown et al., 2014; González et al., 2014; Wishart et al., 2017; González-García et al., 2021; Bates et al., 2023).

Despite the advancements in modelling techniques, there is limited research on the accuracy of sheep LW assessments using MM in the context of WOW and YW comparisons within commercial grazing environments. Brown et al (2012 and 2013) assessed the accuracy of mob-based WOW system estimates compared to flock mean weights from static scales. The strongest agreement ($R^2 = 0.89$) was achieved using a 25% filter and a 1-day grouping strategy with a subjectively chosen central reference weight. The study found a mean difference of just 1.86 ± 0.85 kg between WOW and static scale means, suggesting that, when properly filtered, WOW systems can serve as a highly accurate proxy for average flock weight. This supports the notion that WOW systems, even without identifying individuals, can be valuable for nutritional and health management at the flock level.

However, in a separate study, Brown (2014) highlighted the challenges of achieving precise individual LW measurements using WOW systems. It was determined that more than 11 weight measurements per individual sheep were required to improve precision and reduce the 95%

confidence interval to less than 2kg. In the context of dairy sheep, a study by González-García et al. (2021) confirmed that WOW measurements were in strong agreement with conventional static scales with 0.8kg (95% confidence interval) over estimation of LW between WOW and YW. The findings underscore the potential of WOW systems for livestock weight monitoring but also reveal the need for further refinement and calibration to enhance their accuracy, particularly for individual animals. However, other techniques have also been proposed to analyse WOW and delete outliers based on penalised B-splines in cattle (Gonzalez et al., 2014) albeit this technique has not been evaluated with sheep.

Gonzalez-Garcia et al. (2018) demonstrated a high correlation ($r^2 = 0.93$) between short-term changes in WOW-recorded body weight and actual forage intake, under controlled feeding conditions. This correlation validates the potential of WOW to act as a non-invasive estimator of intake, especially when animals voluntarily access water or minerals via the WOW station. Their results underscore that short-term LW changes, when accurately filtered, are highly reflective of actual intake.

There is a gap in understanding how WOW systems perform in real-world commercial settings over a longer period with various breeds and significantly larger flock sizes. This knowledge gap is significant, as accurate LW measurements are essential for optimizing management decisions, improving production efficiency, and ensuring PLF systems deliver appropriate data for decision making. The hypothesis of the present study was that WOW produces LW estimates not different from YW. Model performance was then quantified by partitioning prediction error into systematic and random components, thereby assessing both bias and unexplained variability.

3.3 Materials and Methods

All experimental procedures were approved by the Institutional Animal Ethics Committee of The University of Sydney (Approval 2020/1730 and 2016/983).

The study was conducted in the Central Tablelands, Riverina and Western regions of New South Wales, Australia. A total of 5,786 paired observations of both WOW and YW from various sheep breeds (Poll Dorset, Merino, Border Leicester) were collected over a period of 4 years. A total of 6 flocks were used to generate the data set (Table 3.1) comprised of 842 ewes, 4737 lambs, and 207 rams. For each of the 6 flocks the same set of animals were allotted to both YW and WOW while in the same paddocks.

The ewes and rams were fitted with an individual EID ear tag prior to entering the trial sites. The lambs in the Orange and Armatree flocks were tagged with an EID within 24 hours post birth with no acclimation period as they followed their mothers into and out of the WOW platform since birth. The lambs in Dubbo, Peak Hill, and Tullamore were not EID tagged until marking up to 6 weeks post birth. All the ewes and rams used tags as part of the commercial farms' management plan over the previous 5 years.

Table 3. 1. Location, attractant type, breed, livestock category and number of observations for trial sites.

Flock Location / attractant	Attractant type	Strain	Livestock category	Observations
Orange	Water, mineral supplement	Poll Dorset	mixed aged ewes	371
Orange	Water, mineral supplement		mixed sex lamb	4,165
Dubbo	Water, mineral supplement	Merino	mixed sex lamb	74
Dubbo	Water, mineral supplement	Merino	rams	152
Peak Hill	Water, mineral supplement grain, hay	Merino	mixed aged ewes	256
Peak Hill	Water, mineral supplement grain, hay	Merino	mixed sex lambs	14
Peak Hill	Water, mineral supplement grain, hay	Merino	ram	55
Griffith	Water, mineral supplement, grain	Merino	ewe hogget	267
Tullamore	Water, mineral supplement	Merino	mixed aged ewe's	215
Tullamore	Water, mineral supplement	Merino	mixed sex lamb's	151
Armatree	Water, mineral supplement	Border Leicester	mixed sex lamb	1
Camden	Water	Merino	Ewes	65
Total				5,786

Yard Weight

The flocks were moved from the paddock to the sheep handling facilities (< 6 km away) in all locations to record YW to coincide with the producer's normal health and welfare checks or animal management procedures (drenching, marking, weaning, shearing). In the context of commercial application, variations in management practices among producers led to the use of different methodologies for measuring YW, each aligned with individual operational plans and tailored to specific on-farm requirements. Producers used various designs of YW platforms, some that were commercially available, or "home" built with commercial weighing technologies.

Each individual sheep was caught within a standalone weigh crate to record individual animal YW data. The weight platforms for YW were checked throughout each assessment for reliable data collection by zeroing the scale and weighing a human of known weight. The YW data was presented to the research team in an Excel file format (EID, Date, LW) by the producer. None of the sheep had access to feed or water whilst they were being held in the yards prior to weighing.

Walk Over Weighing Set Up

The lambs were born while the dams were already using the WOW system, so they were introduced to the WOW by the ewes as part of the grazing enterprises. The WOW station was setup at the entrance and exit of a yard enclosing an attractant, so the WOW data was recorded as the sheep passed over a WOW platform to access an attractant(s) (water, mineral supplement, grain, hay) within the paddock.

Animals traversed back (entry) and forth (exit) over the platform when the data collection system recorded EID, date, time, and weight (kg). Data recording equipment for the WOW electronic components included a WOW indicator (model WOW2; Tru-test, Mount Wellington, New Zealand), connected to load bars (model MP600; Tru-test, Mount Wellington, New Zealand) mounted on a platform and an EID reader (model XRP2; Tru-test, Mount Wellington, New Zealand) which was connected to a small antenna (Tru-test, Mount Wellington, New Zealand). This equipment was powered by two 105 Amp deep cycle batteries (Century Yuasa Batteries, Carole Park, Queensland 4300, Australia) charged using a 240-watt Solar panel (SRGS Pty Ltd, Strathpine, New South Wales, Australia). The recording equipment was attached to a uniquely developed platform which were moved from paddock to paddock as the sheep were moved by the producer. Raw data was collected and stored by the WOW and then routinely (minimum twice a week) uploaded to a server at the University of Sydney using a 3G modem (Maxon Australia, Seven Hills, New South Wales, Australia).

Data Handling

Each observation included time stamp, animal EID, and information including farm identification, WOW station number, and flock name (if applicable) to ensure traceability and reliability. Data only

from sheep that traverse the WOW are included in the analysis. The raw data includes outlying data points. The WOW data was processed as described by Gonzalez et al. (2014) using penalised B-splines, and outliers deleted if they fell outside the mean by ± 1.5 standard deviations of the predicted LW. The WOW and YW datasets were merged by EID and date. Descriptive statistics, including mean, standard deviation (SD), maximum, and minimum values were computed for both WOW and YW. The normality of the data for the independent (WOW weight) and the dependent variable (YW) was assessed using the Shapiro-Wilk test (Shapiro & Wilk, 1965).

Statistical analyses were conducted to evaluate agreement between WOW (x-axis) and conventional YW (y-axis) and to assess the suitability of WOW for LW monitoring under commercial grazing conditions. Linear regression was used to quantify the strength of association between WOW and YW measurements, the deviation from the perfect fit (intercept = 0; slope = 1), with precision through the coefficient of determination (R^2), Lin's concordance correlation coefficient, mean bias, systematic bias, and error decomposition (Tedeschi et al., 2006).

Error analysis was conducted to quantify predictive accuracy and identify sources of bias. The RMSE and Mean Square Error of Prediction (MSEP) were calculated to measure the average prediction error. Mean bias, systematic bias, and random error were analysed per established methods (Dent & Blackie, 1979). Mean bias quantified the average deviation between predicted and observed values, whereas the systematic bias was used to assess consistent trends in prediction errors across the dataset. Random error was expressed as a percentage of the total error to highlight variability not attributable to mean or systematic factors.

A balance analysis was performed following the framework established by Tedeschi et al. (2006) to compare predicted and observed outcomes across below- and above-threshold categories.

3.4 Results

Statistical comparisons between YW and WOW for the sample of 5,786 observations are presented in Table 3.1. The mean recorded YW was 2.83 kg (mean bias) lower than the WOW weight (Table

3.2). However, the maximum and minimum YW were 6.13 and 2.41 kg/hd lower in YW compared to WOW weight, respectively (Table 3.2) with WOW explaining 89% of the variability in YW. However, the LCCC values was strong.

Figure 3.1 shows a strong linear relationship between YW and WOW predicted weight. The intercept was small but greater than the ideal of zero ($P < 0.001$) and the slope smaller than the ideal unity ($P < 0.001$; Table 3.2). Importantly, the accuracy coefficient (bias correction factor) was close to unity (Table 1). The WOW data showed a significant mean bias overestimating YW ($P < 0.001$; Table 3.2) and systematic bias ($P < 0.001$) albeit both biases accounted for a minor proportion of the error whereas 82% of the error was random (Table 3.2).

Table 3. 2 Results of the adequacy of walk over weighing (x; WOW) to predict yard weight (y) in grazing sheep.

	Yard Weight (Y)	WOW Weight (X)
Adequacy statistics		
Mean	41.51	44.34
SD	23.15	24.08
Maximum	122.00	128.13
Minimum	2.50	4.91
n	5786	5786
R ²	0.889	
LCCC	-	0.935
Cb	-	0.992
Linear Regression Analysis		
Intercept (a)	-	1.321
SE of the intercept	-	0.212
P-value (a = 0)	-	<0.001
Slope (b)	-	0.906
SE slope	-	0.004
P-value slope (b = 1)	-	<0.001
Mean Square Error of Prediction Analyses		
RMSE, kg/hd	-	7.730
RMSE, % observed	-	18.62
MSEP	-	72.896
Mean bias, kg/hd	-	-2.838
Mean bias, % of observed	-	-6.839
Mean bias P-value	-	<0.001
Systematic (linear) bias	-	0.0938
Systematic (linear) bias SE	-	0.0042
Systematic (linear) bias P-value	-	<0.001
MSEP decomposition		
Mean bias, % of total error	-	11.055
Systematic bias, % total error	-	6.998
Random error, % total error	-	81.945

SD: standard deviation; n: number of animals in the analysis; R²: R-squared; LCCC: Lin's concordance correlation coefficient; Cb: bias correction factor; SE: standard error; RMSE: root mean square error; MSEP: mean square error of prediction.

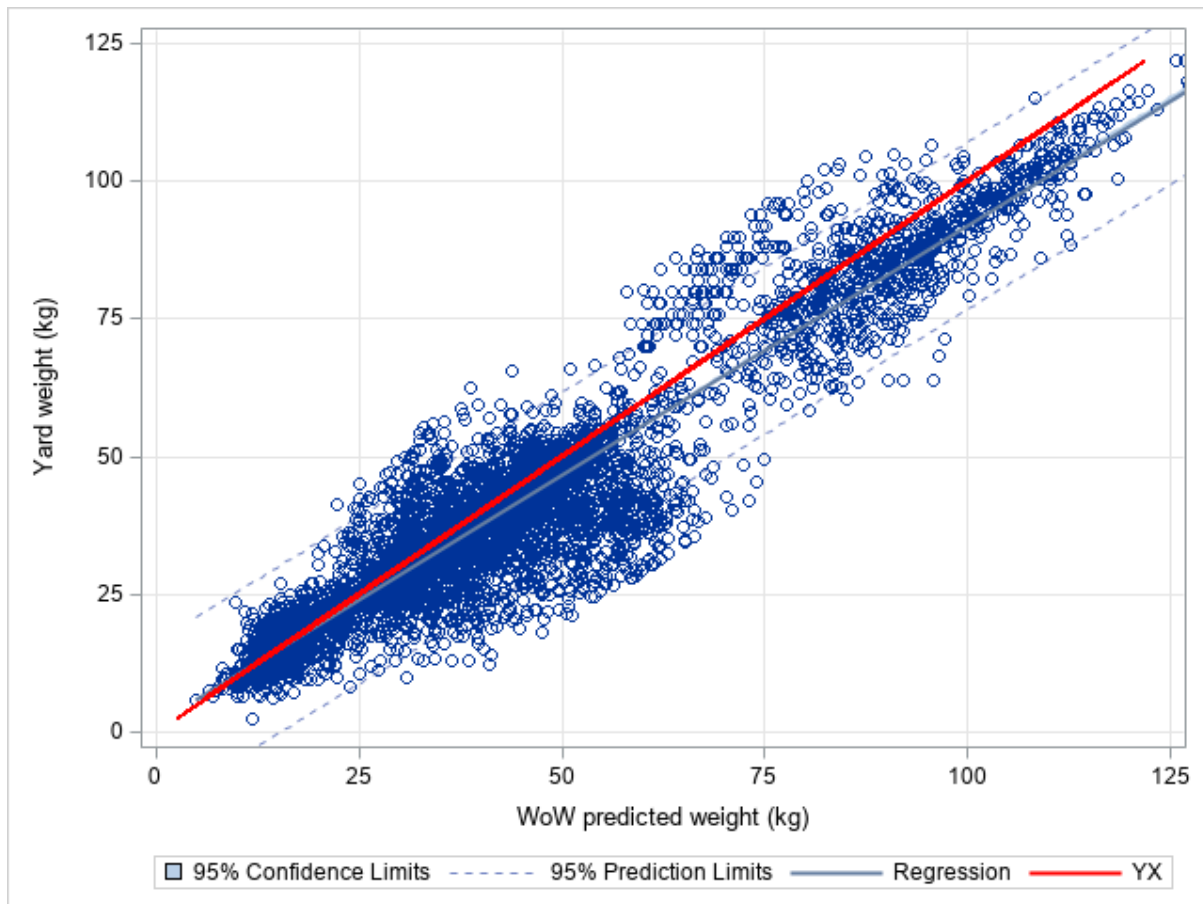


Figure 3. 1 Linear regression between walk-over-weighing predicted weight and yard weight (kg). The blue line is the least-squares regression (95 % CI in grey), dashed blue lines are 95 % prediction limits, and the red line is the identity ($y = x$).

For below-threshold predictions (data not shown), the model overpredicted 34.19% of datapoints and underpredicted 25.65% compared to the observed values of 42.03 and 19.74%, respectively. For above-threshold predictions, the model overpredicted 31.35% of cases and underpredicted 8.81%, whereas the observed data showed 23.51 and 14.73%, respectively.

Under balanced allocation, χ^2 tests (below: $\chi^2 = 895.95$; above: $\chi^2 = 985.03$; both $P < 0.001$) strongly reject independence, with moderate association (Cramér's $V = 0.393, 0.412$) and concordance (CCC = 0.366, 0.381). Using the observed, imbalanced class distribution, χ^2 remains significant (below: $\chi^2 = 269.46$; above: $\chi^2 = 26.07$; both $P < 0.001$) but association ($V = 0.215, 0.067$) and Lin's concordance (LCCC = 0.210, 0.066) dropped markedly. The odds ratio analysis revealed that below-threshold

predictions were underestimated (OR=0.374, while above-threshold predictions were overestimated (OR=1.334).

3.5 Discussion

The findings of the present study demonstrated strong predictive performance of WOW data, underscoring its utility of WOW compared to YW. There were significant mean and linear biases, albeit these contributed to less than 20% of the total observed error. The predominance of random error, rather than mean and systematic error, suggested that the observed discrepancies were largely attributable to inherent biological and environmental noise rather than flaws in the WOW system. The mean bias indicated that WOW overestimated LW measured in the yards. Several reasons are plausible for these results including yard weight being measured after mustering and animals being held in the yards with no feed and water and emptying of the gastrointestinal tract. Therefore, the mean bias may not necessarily reflect inaccurate WOW data but true differences in animal weight in the paddock (WOW) and the yards (YW).

Accurate LW estimation is critical for optimizing feeding strategies, estimating growth rate, and ensuring efficient resource utilization in livestock operations (Gonzalez et al., 2018 & 2022). The strong LCCC values indicate that the hardware, equipment setup, and analytical method capture sufficient variability in observed LW, providing a valuable tool for decision-making.

The WOW data tended to overpredict outcomes in both below and above categories, requiring further refinement to enhance prediction accuracy. The strong linear relationship between WOW and YW, with most observations within the 95% prediction limits, indicate that the WOW technology and accompanying analytical method captures the variability in the data well. However, the positive linear bias suggests that the predictions are less accurate at heavier weights.

Results of the present study are slightly more precise than those presented by Brown et al. (2012) for mob-based WOW estimates ($R^2 = 0.80$) which could be because the present study used data from individual animals and a different data processing method.

However, the observed biases and deviations from proportionality suggest that refinements to the WOW data are necessary to enhance its accuracy and applicability. Our results are similar to earlier research outcomes as expected that the slope's deviation from unity indicates that the relationship between WOW and YW is not perfectly proportional (Brown et al., 2014; González et al., 2014; Wishart et al., 2017; González-García et al., 2021; Bates et al., 2023).

The balance analysis, following the approach of Tedeschi et al. (2006), demonstrated that the model possesses a measurable capacity to distinguish between LW categories, particularly under balanced allocation conditions. Moderate agreement was observed, with Cramer's V values ranging from 0.39 to 0.41 and CCC values exceeding 0.36, suggesting that the model successfully captures underlying trends in the data. Classification strength under current allocation conditions was lower, with reduced Cramer's V (0.067–0.215) and CCC (0.066–0.210), this reflects the model's sensitivity to real-world variability rather than fundamental flaws. Importantly, the odds ratio (OR = 1.33, $P < 0.001$), supporting the model's potential to identify meaningful patterns under field conditions. The predominance of random error, rather than systematic bias, suggests that predictive accuracy can be enhanced through targeted refinements such as incorporating additional biological or environmental predictors, WOW system setup, or improving sensor calibration.

The balance analysis results highlight the importance of evaluating model performance under different allocation scenarios. Refining the model to reduce overprediction and underprediction biases will be crucial for ensuring its applicability in real-world contexts. For instance, imbalances in data distributions can influence prediction performance, particularly when predictions are made outside the range of the training data (Gao et al., 2025). Addressing these issues through data augmentation or advanced calibration methods can help mitigate systematic biases and improve reliability.

The robust performance of the WOW data and associated analytical method in the present study demonstrates its utility and accuracy for analysing large datasets and identifying key factors

influencing LW. By leveraging these tools, producers can gain deeper insights into animal performance, enabling the development of more effective and sustainable management practices.

Addressing the sources of error through improved calibration procedures and consistent measurement protocols could enhance the WOW system performance (Brown et al., 2012; Brown et al., 2014; Gonzalez Garcia et al., 2018). The WOW and YW systems were calibrated sporadically in the present project. It is also important to note that the present study was performed under commercial conditions and thus the weighing procedures were not standardised, especially the time elapsed between mustering the animals from the paddocks, yarding time, and weighing and the time off feed and water, as well as the environmental conditions during that time. The variability of the time elapsed between the last WOW and YW record was not considered in the present analysis. These factors are known to affect LW loss (shrinkage) due to defecation, urination, and dehydration so a shorter time between WOW and YW could improve the agreement between both measurements.

However, the strong R^2 and LCCC, and low errors due to mean and linear bias reported in the present project suggest that the WOW is a valuable tool for predicting sheep weight, with potential applications in nutritional management, market classification, and production optimization. This is important because the present study seems to be the first published study performed in a multi-site fashion under commercial conditions. To further enhance the accuracy of the WOW system, refinements to reduce systematic and mean biases reducing the time between WOW and YW records, incorporating additional variables to the model, or recalibrating weighing systems could be explored.

Accurate weight estimation is critical for optimizing feeding strategies, monitoring growth rate, and managing feed resources efficiently in livestock operations. The ability to predict YW with reasonable accuracy using WOW systems can streamline on-farm operations, reducing the need for more labour-intensive or invasive measurement techniques (Brown et al., 2013).

The WOW can enable early intervention and more responsive management including feeding strategies. The results of the present study highlight the capacity of precision livestock technologies, such as the WOW systems, to generate accurate, high-frequency data that can be integrated into predictive models for targeted management (i.e. nutrition, reproduction, growth, reduced mortality).

3.6 Conclusion

This study demonstrated sufficient accuracy and precision of WOW systems in extensive sheep production systems to inform management practices that improve their productivity, profitability, and sustainability.

These findings have important implications for the deployment of WOW systems as part of the PLF approach, particularly as this relates to the validity of automated data streams for real-time monitoring and decision-making. The results in the present study support the integration of automated weight monitoring into larger modelling frameworks for flock management, forecasting, and health surveillance.

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3.8 Data Availability Statement

Data available on request from L.A.G. due to restrictions.

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3.10 Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study nor in the collection, analyses, or interpretation of data or in the writing of the manuscript.

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Chapter 4

Remote monitoring of liveweight in pregnant and lactating Poll Dorset ewes.

4.1 Abstract

Remote monitoring of liveweight (LW) and average daily gain (ADG) in late pregnancy and lactating ewes in grazing conditions could be used to predict and manage ewe reproductive performance. The present study examined a total of 315 artificially inseminated Poll Dorset ewes over 143 days for two lactations. Liveweight data was obtained with walk-over weighing (WOW) stations set up in the paddock. Yard data was collected at day seventy of pregnancy to include the number of foetuses scanned per ewe. The objective of the study was to analyse differences in remotely collected LW and ADG in artificially inseminated ewes bearing single or twin foetuses (scanned litter size; SLS). Mixed-effects models were used with LW or ADG as the dependent variable, date, scanned litter size (single or twin) and their interactions as fixed effects, whereas animal ID was the random factor. The SLS × date interaction affected LW both years ($P < 0.05$) with the LW of single and twin-bearing ewes in late gestation being similar in 2021, but twin-bearing ewes were heavier than single-bearing ewes in 2022 ($P < 0.05$). In addition, twin bearing ewes took longer to start gaining LW late in lactation compared to single bearing ewes. In contrast, SLS × date interaction affected ADG in 2021 ($P < 0.001$) because single-bearing ewes had greater ADG compared to twin-bearing ewes after the nadir ADG from the middle of gestation, but no interaction existed in 2022 ($P = 0.999$). This study demonstrated that remote monitoring of LW and ADG using WOW stations is possible under commercial grazing conditions and provides data to manage and monitor reproduction.

Keywords: ewes, reproduction, liveweight, growth, walk over weighing

4.2 Introduction

Precision livestock farming (PLF) has the potential to improve the efficiency of production systems (Banhazi & Black, 2009). Modern agricultural technology continues to be improved with remote access to livestock performance and behaviour, and as such livestock producers now have more advanced management tools available, with information accessible from any electronic device (Banhazi et al., 2011). The collection and analysis of data, however, requires automation, interpretation of the measurements, identification of critical measurement limits, and built-in automatic control systems to optimise production systems (Gonzalez-Garcia et al., 2018). The use of in-paddock walk-over-weighing (WOW) platforms is a PLF technology that allows automation of livestock LW data collection and analysis (González et al., 2014).

These data provide a suite of information to target animal performance at an individual level and thus allows the producer to optimise key management decisions (Morgan-Davies et al., 2015). These remote weighing systems rely on electronic identification (EID) ear tags of individual animals, tag reader, a platform with load bars, and a data recording and transmission system (Atkins et al., 2006; Brown et al., 2014; González et al., 2014; Morgan-Davies et al., 2015).

Ewe's individual LW and ADG during late pregnancy and lactation is not normally recorded on farms because of labour and livestock stress associated with mustering from the paddock and handling in the yards, especially during stressful periods such as late pregnancy or lactation with newborn lambs at foot (Wang et al., 2022). Monitoring liveweight (LW) changes during pregnancy and lactation may facilitate the detection of health and welfare issues including, but not limited to, abortion, parasites, nutritional deficiencies, and survival of newborn lambs and ewes. Brown et al. (2012; 2013), Leroux et al. (2023), and Bates et al. (2023) presented WOW systems to collect LW data for subsequent ADG analysis. Similarly, Wishart (2019) concluded that WOW is a suitable tool for monitoring sheep behaviour in grazing environments.

However, despite the importance of this information in improving reproduction and reducing reproductive losses, no published data could be found on the LW changes and growth patterns of pregnant and lactating ewes using WOW in commercial grazing operations.

The objective of the present study was to determine if remotely collected LW and ADG is affected by SLS in Poll Dorset ewes under commercial grazing conditions from late gestation through to lactation.

4.3 Materials and Methods

All experimental procedures were approved by the institutional Animal Ethics Committee from The University of Sydney (Approval 2020/1730 and 2016/983). The study was undertaken near the town of Orange within the Central Tablelands region of New South Wales, Australia. The average monthly rainfall during the study period was 80.4 mm from 1st of May to 30 September, average daily maximum temperature was 11.9 °C and minimum of 3.0 °C (Bureau of Meteorology, 2024).

Two cohorts of mixed aged, pregnant Poll Dorset ewes were monitored from late pregnancy to weaning (1st April to 20th August) in 2021 and 2022. Pregnancy diagnosis and approximate date of joining was undertaken twice via transabdominal ultrasonography at 70 and 98 days after artificially inseminated (AI). This trial is researching outcomes in AI ewes only; hence, those ewes that were determined (foetal size) to be AI via the ultrasound assessment were kept in this trial. The pregnancy scanning records from day 70 of pregnancy only were used in the analysis. The same pregnancy scanning technician was used for both years.

The percentages of ewe age and total number per year of artificially inseminated ewes used for the final analysis is provided in Table 4.1. All ewes involved in the trial were fitted with a unique EID (Shearwell Australia Pty Ltd; Bendigo, Victoria 3550 Australia).

Table 4. 1 Number of ewes (%) monitored for liveweight using remote walk-over-weighing in two consecutive pregnancy and lactation periods.

Age of Ewe (years)	2021		2022		Total
	Single	Twin	Single	Twin	
2-year-old	1 (1.4%)	0 (0.0%)	3 (4.1%)	1 (1.1%)	5 (1.5%)
3-year-old	18 (26.0%)	15 (17.0%)	38 (52.0%)	48 (54.5%)	119 (37.7%)
4-year-old	15 (21.7%)	25 (29.0%)	18 (24.6%)	16 (18.1%)	74 (23.4%)
5-year-old	27 (39.1%)	34 (40.0%)	14 (19.1%)	23 (26.1%)	98 (31.1%)
6-year-old	8 (11.5%)	12 (14.0%)	0 (0.0%)	0 (0.0%)	20 (6.3%)
Total	69	85	73	88	315

Lambing of AI ewes took place from 30th April 2021 to 16th May 2021, and 1st May 2022 to 14th May 2022. Inspection of the lambing ewes were undertaken twice daily by the producers and their staff. Lamb loss between lambing and weaning was 6.8% in 2021 and 5.6% in 2022 for twin born lambs, and for singles was 2.7% in 2021 and 6.9% in 2022 (Table 4. 2).

Table 4. 2 Pregnancy, lambing and weaning information of artificially inseminated ewes with liveweight monitored remotely during late gestation and weaning in two different years.

	2021	2022
Ewes	154	161
Singles foetuses scanned	69	73
Twin foetuses scanned	170	176
Pregnancy scanning percentage	155.1	154.6
Single lambs born	72	73
Twin lambs born	174	177
Lambing percentage	159	155
Single lambs weaned	67	71
Twin lambs weaned	162	167
Weaning percentage	148	147.8
Single lamb weaning LW*, kg	46.18	48.78
Twin lamb weaning LW*, kg	35.84	36.63

* LW – Animal Liveweight

The flock was grazed rotationally across 11 paddocks, totalling 178 ha. Each paddock ranged between 8 and 40 ha and contained predominantly vetch (*Vicia spp.*), rye grass (*Lolium perenne*), subterranean clover (*Trifolium subterraneum*), phalaris (*Phalaris canariensis*) and lucerne (*Medicago sativa*). The early lambing paddocks contained oats (*Avena sativa*), native pasture and lucerne. Paddocks used for mid to late lactation contained mainly subterranean clover, lucerne, ryegrass, and phalaris. In 2022, ewes and lambs also had a vetch and subterranean clover to graze for six weeks starting four weeks before the beginning of lambing. In 4 of the 11 paddocks used, loose mineral lick was the only attractant for the ewes to entice them into the WOW station. The remaining seven paddocks contained a WOW station placed at the water trough which also included loose mineral lick.

The loose molasses granular lick feed is commercially available (NUTRI-mins Ewe and Lamb, Advanced Animal Nutrition Pty Ltd, Forbes, New South Wales, Australia). The composition of this supplement was Vitamin A (0.250 MIU), Vitamin D (0.05 MIU), Vitamin E (0.750 g/kg), Cobalt (0.08 g/kg), Iodine

(0.03 g/kg), Selenium (0.01 g/kg), Potassium (0.2%), Iron (2.5 g/kg), Magnesium (15%), Manganese (4 g/kg), Sulphur (0.3%), Zinc (3 g/kg), Salt (30%), Phosphorus (4.8%), and Calcium (18%) with molasses making up the balance.

Walk Over Weighing (WOW) stations

The development of the WOW system used in the present study continued from previous research undertaken in cattle (Gonzalez et al., 2014). The WOW platform was built with a steel frame (1.2 m long × 1 m height × 0.6 m width) and mounted on a wooden platform bolted onto two load bars (MP600, Tru-test Scandinavia, Præstø, Denmark), a walk-over weighing indicator (WOW2, Tru-test Scandinavia, Præstø, Denmark), and EID reader (XRP2, Tru-test Scandinavia, Præstø, Denmark) which was connected to a small antenna (Tru-test Scandinavia, Præstø, Denmark). The system recorded individual EID, weight, and date and time as the animals walked over the platform. The data was transmitted to a server using a 3G modem (Maxon Australia, Seven Hills, New South Wales, Australia) connected to the WOW2 indicator. The WOW station was powered by two 105 Amp deep-cycle batteries (Century Yuasa Batteries, Carole Park, Queensland 4300, Australia) charged using a 240-watt Solar panel (SRGS Pty Ltd, Strathpine, New South Wales, Australia). All electronic components were enclosed in a plastic container to protect them from the weather.

The ewes entered and exited the yards containing the attractant by walking through the WOW station to access water or mineral attractant provided to allow for ad-libitum consumption.

The WOW stations were placed two months before the expected lambing start date to habituate ewes to accessing the platform. Liveweight data of ewes was analysed from 1 month before lambing (1st April 2021 and 1st May 2022) until weaning at approximately 16 weeks after the start of lambing.

Data processing and statistical analysis

The LW data collected was processed to eliminate outliers and obtain predicted LW and ADG using penalised b-splines as described by Gonzalez et al. (2014). In addition to deleting all pregnant ewes from natural joining, AI ewes with triplets or quadruplets were also deleted from analysis because of

the low number of animals for meaningful comparisons. Ewes with fewer than 80 days of LW data out of the 143-days of trial duration were also deleted from analysis for a robust analysis of SLS.

Chapter 4 employed linear mixed-effects models to analyse longitudinal ewe LW and ADG across late pregnancy and lactation. Ewe identification was included as a random effect to account for repeated measurements within individuals and to appropriately model within-animal correlation. Fixed effects included scanned litter size (SLS), date, and their interaction, reflecting biologically plausible differences in energetic demand across reproductive states.

Model assumptions were evaluated using residual diagnostics, and alternative random-effect structures were explored to confirm stability of fixed-effect estimates.

4.5 Results

Predicted LW values ranged from 67.92 to 125.75 kg, with single-bearing ewes generally showing higher averages in both years compared to twin-bearing ewes (Table 4.3). In the absence of statistical testing, these average differences should be viewed as descriptive only, and their biological significance cannot be confirmed. The standard errors for LW were low (0.96–1.28 kg), indicating precise estimates. ADG ranged from -0.898 to 0.410 kg/day, with negative average values for all groups, suggesting slight weight loss overall. Twin-bearing ewes exhibited marginally lower average ADG compared to single-bearing ewes across years. Standard errors for ADG were stable at 0.027–0.118 kg/day.

Table 4. 3 Summary statistics of predicted liveweight and average daily gain of ewes measured with remote weighing systems.

	2021		2022	
	Single	Twin	Single	Twin
Predicted Liveweight, kg/hd				
Minimum	67.92	77.01	72.16	73.6
Maximum	115.07	125.75	117.32	115.45
Mean	92.98	96.35	95.27	95.58
Medium	94.75	94.93	97.76	95.26
Stand Deviation	9.44	10.66	9.42	9.01
Standard Error	1.03	1.28	1.1	0.96
Average daily gain, kg/d				
Minimum	-0.624	-0.792	-0.898	-0.762
Maximum	0.141	0.345	0.239	0.41
Mean	-0.248	-0.209	-0.161	-0.13
Medium	-0.24	-0.168	-0.151	-0.132
Standard Deviation	0.169	0.224	0.216	0.180
Standard Error	0.018	0.027	0.025	0.019

The SLS × date interaction affected LW in both years and ADG in 2021 ($P < 0.05$; Table 4.4) but not ADG in 2022 ($P > 0.05$ Table 4.4) when only date effected ADG ($P < 0.05$ Table 4.4).

Table 4. 4 Effect of scanned litter size factor, date factor and the interaction on predicted liveweight and average daily gain.

	2021		2022	
	F-value	P-value	F value	P-value
Predicted Liveweight, kg/hd				
Scanned litter size	3.135	0.046	0.323	0.723
Date	85.100	<0.001	39.15	<0.001
Scanned litter size × Date	2.830	<0.001	1.164	0.013
Average Daily Gain, kg/d				
Scanned litter size	0.098	0.906	0.151	0.859
Date	22.764	<0.001	13.426	<0.001
Scanned litter size × Date	2.993	<0.001	0.811	0.999

Least square means of the SLS × date interaction on LW is shown in Figure 4.1 for both years. In 2021, both single- and twin-bearing ewes had similar LW in late gestation prior to the start of

lambing ($P > 0.05$; Figure 4.1 top panel). However, twin bearing ewes started showing lower LW compared to single bearing ewes as lambing approached and progressed, and the difference between them became larger throughout lactation ($P < 0.05$). Both single and twin bearing ewes decrease LW throughout the first 2 months of lactation in 2021 when the largest difference in LW between groups occurred ($P < 0.05$). After this period, LW of both single and twin bearing ewes started to increase although twin bearing ewes continued showing lower LW compared to single bearing ewes until weaning ($P < 0.05$; Figure 4.1 top panel).

In 2022, predicted LW of twin-bearing ewes were 2.6 kg/hd heavier than single-bearing ewes in late gestation but 5.1 kg/hd lighter in late lactation before weaning (Figure 4.1 bottom panel). Both single and twin bearing ewes gained weight during late gestation prior to the expected lambing start date on 1st of May ($P < 0.05$) and reached their lowest LW in early July. Furthermore, the LW decline was sharper for both ewe groups and the recovery of LW was less pronounced in 2022 compared to 2021, particularly for twin bearing ewes which showed no increase in LW during lactation.

Figure 4.2 shows the predicted ADG of single versus twin-bearing ewes during late gestation and lactation for 2021 (top panel) and 2022 (bottom panel). In 2021, both single and twin bearing ewes showed a steep decline in predicted ADG after the start of lambing on the 1st of May ($P < 0.05$) and remained negative (losing LW) until approximately 60 days from start of lambing (Figure 4.2 top panel). The fastest LW loss (lowest ADG) was observed in the middle of May when the lambing period was finished and twin bearing ewes having lower ADG compared to single bearing ewes until the end of June ($P < 0.05$).

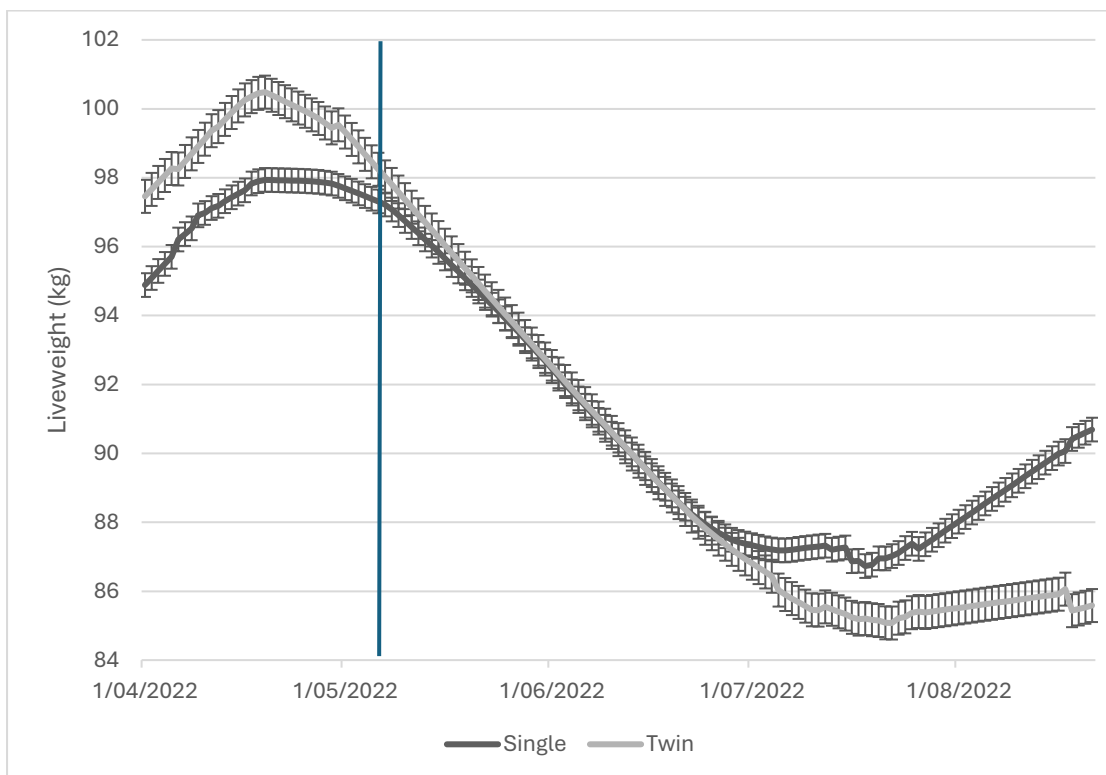
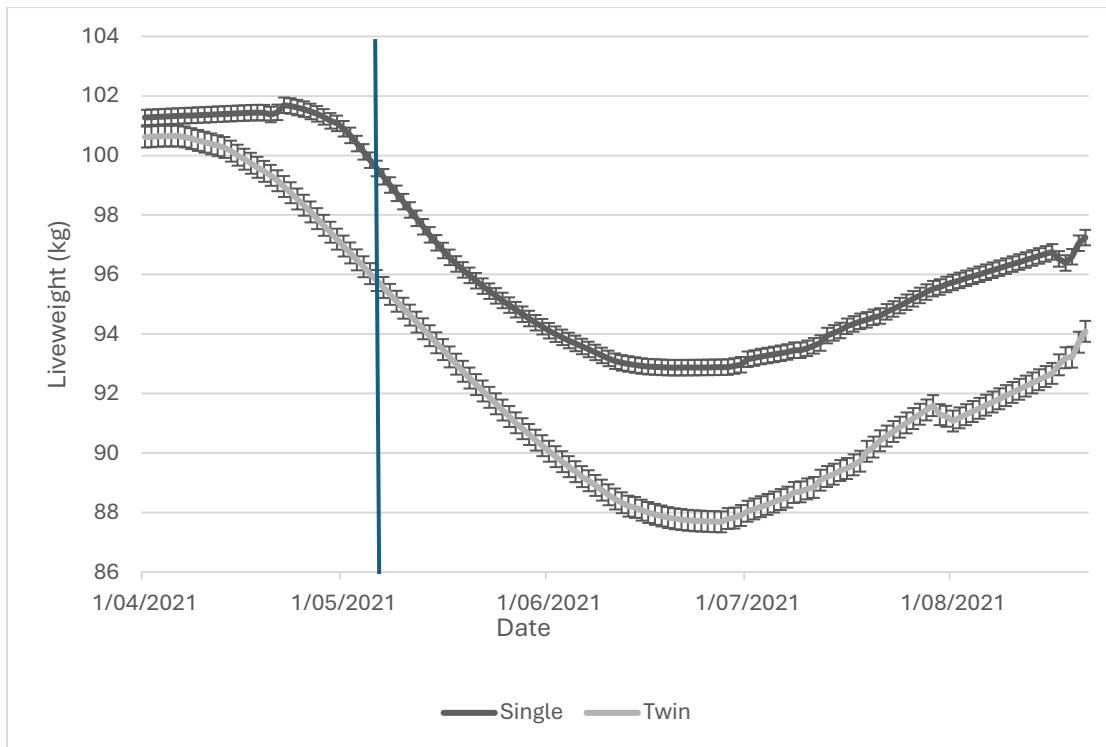


Figure 4. 1 Predicted liveweight of single and twin bearing ewes during late gestation and lactation in 2021 (top panel) and 2022 (bottom panel). Average lambing date is identified as solid vertical line.

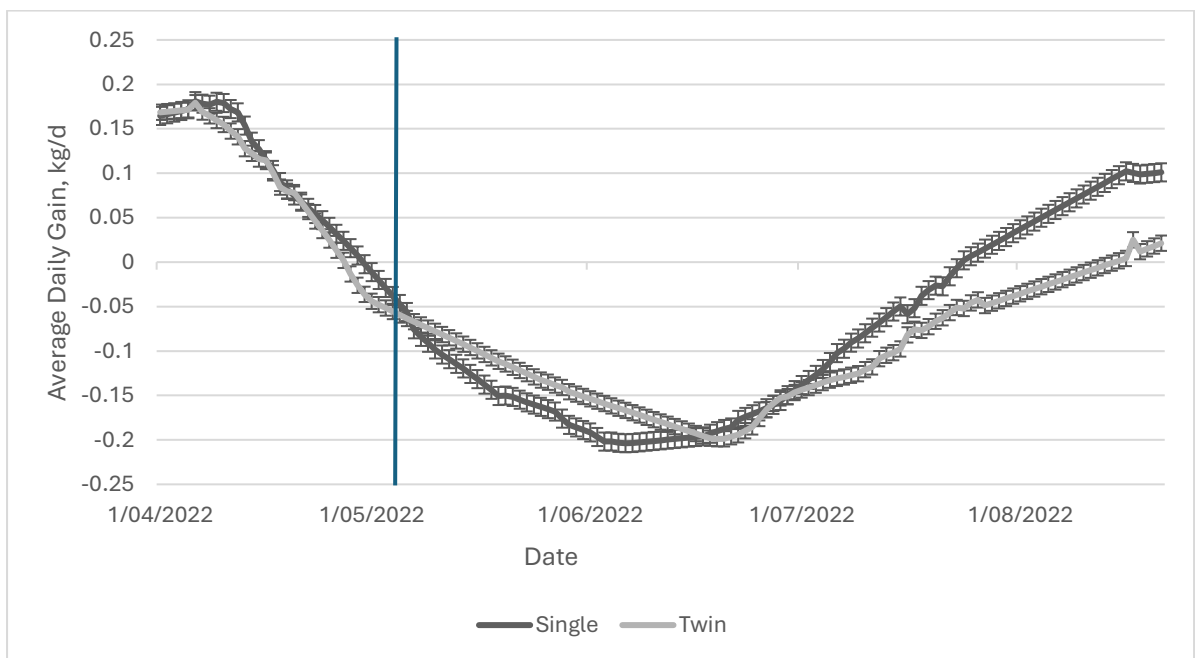
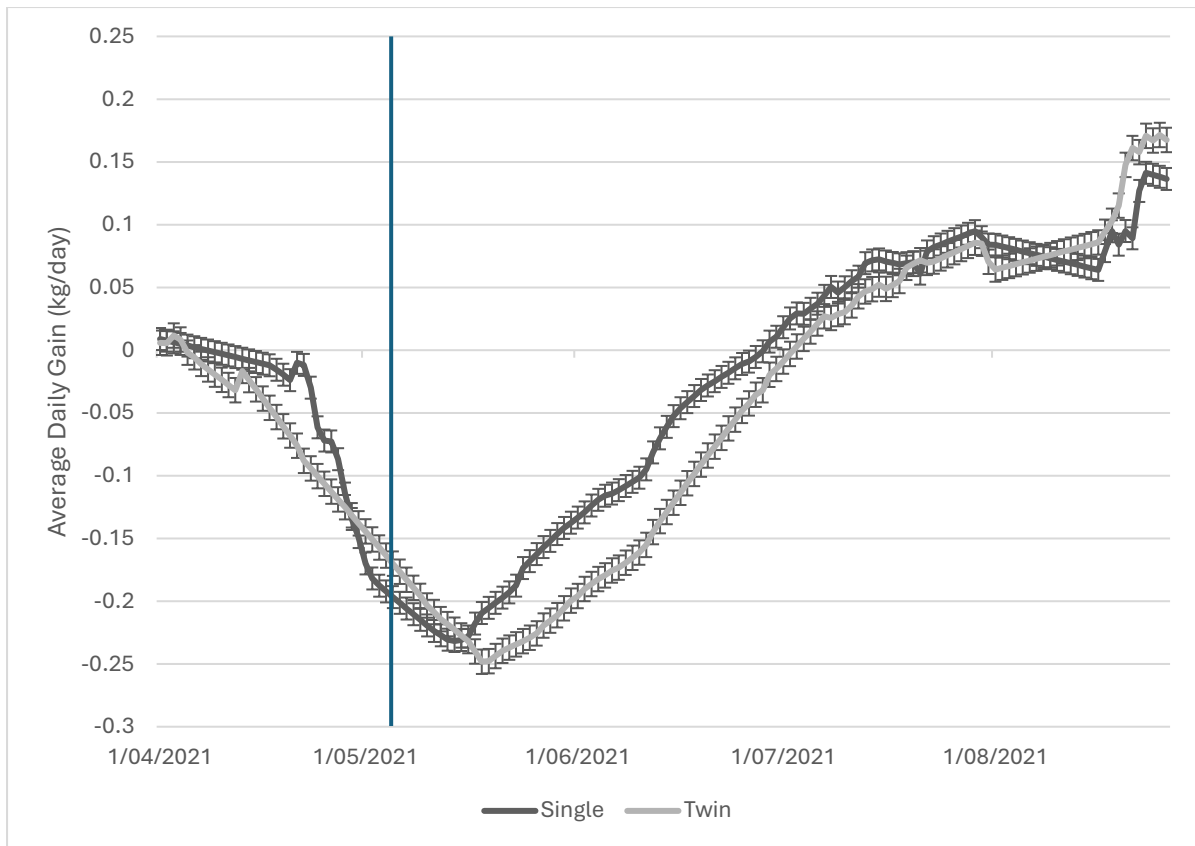


Figure 4. 2. Predicted average daily gain of single and twin bearing ewes during late gestation and lactation in 2021 (top panel) and 2022 (bottom panel). Average lambing date is identified as solid vertical line.

In 2022, predicted average daily gain was only affected by date ($P < 0.001$) but not by SLS or its interaction with date ($P > 0.05$), which contrasts the results in 2021.

Additionally single and twin-bearing ewes experienced a sharp decline in ADG from a positive ADG of approximately 0.17 kg/d in late gestation to a negative ADG of approximately 0.20 kg/d in June. Twin bearing ewes started to have positive ADG approximately 20 days later than single bearing ewes at the end of lactation although both twin and single bearing ewes had similar ADG from late gestation until late lactation. Overall, the ADG in 2022 showed a similar trend to 2021, with a period of positive ADG during late gestation, negative ADG since the start of lambing through to mid lactation followed by a recovery during late lactation.

4.6 Discussion

The need for effective livestock monitoring of LW and ADG for applications to improve production, health and welfare of livestock is amplified by the inherent challenges of grazing environments (Rivero et al., 2022). The application of digital technologies to monitor and assess livestock performance and behaviour in extensive systems remains underutilized, representing a significant opportunity for future development (Fogarty et al., 2018). Curti et al. (2023) noted that advancements in computing power, data capture, storage capabilities, and cloud computing have significantly accelerated the development of various technologies in recent years. As such, the monitoring of livestock for precision livestock management continues to improve as demonstrated in the present study.

The present study demonstrated that remote monitoring of LW and growth of ewes under grazing conditions in commercial farms is possible with the use of WOW technologies. It has also been proven that the associated data analysis provides unique and valuable information about the physiological state and reproductive outcomes of a commercial flock. This information could be used for multiple applications such as nutritional management, monitoring reproductive success or failure, and genetic selection amongst others. Our study built on previous published research into

remote monitoring of LW on sheep (Brown et al., 2014; González et al., 2014; Morgan-Davies et al., 2015; Wishart, 2019; Bates et al., 2023; Leroux et al., 2023;). However, this seems to be the first published study providing new evidence that WOW systems can remotely detect changes of LW in pregnant and lactating Poll Dorset ewes on a daily basis in near real-time. No known previous research has been published using remote monitoring of ewes' LW and ADG daily throughout late pregnancy and lactation.

Similar figures as those shown in the present paper were made available in near real-time to procedures via a web interface to facilitate monitoring and management. Scanned litter size data was collected using ultrasound scanning by the producer in the handling facilities (yard data). This yard data was then merged with remotely collected LW data to display the information in an appropriate way for the end-user to observe LW and ADG changes over time. Therefore, data recording from multiple sources either remotely using technology or traditional in the yards needs to be integrated to extract more value from these technologies at present.

The recent requirements of mandated EID utilisation of sheep in Australia are expected to increase data collection and the use of new technologies such as WOW. This is expected to promote the adoption of new technologies however, applications of the data to improve productivity, health and welfare, profitability and suitability need to be demonstrated. The present research further exhibits the potential of WOW technology for enhancing monitoring of LW in individual animals in real-time in relation to reproductive outcomes, i.e. gestation and lactation in relation to the number of foetuses scanned.

The WOW systems used in the present study allowed data collection and analysis without the need to move heavily pregnant and lactating sheep from their paddock. Walkom & Brown (2016) highlighted that a single adult static weight measurement is insufficient to fully understand genetic relationships between weight, body condition score, and key traits such as lamb growth, reproduction, carcass, and wool. Brown et al. (2012) evaluated the repeatability of WOW

measurements in individual sheep and Brown et al. (2014) evaluated the use of mob-based WOW in sheep. However, the present study monitored LW of individual ewes throughout an entire lactation, used different algorithms to process the WOW data, and a distinctive design and setup to collect LW data and analyse for longer periods of time.

A goal of using WOW in the present study was to provide information to producers so they can develop a clearer understanding of the physiological state of their flock and the progress of the lambing season. This could result in reduced labour and improved decision-making related to productivity, stocking rates, and animal welfare (Caja et al., 2020). Future research using WOW is encouraged to assess the potential of the technology for automated phenotyping and genetic associations throughout the production cycle, without increasing undue stress on the animals. In addition, the discovery of new phenotypic traits to use in genetic selection could be facilitated by WOW technology such as the extent of LW loss during lactation. However, these potential applications should be investigated further.

Earlier research by González et al. (2023) discussed the prediction of metabolizable energy for maintenance requirements for livestock from LW, activity, and environmental conditions predicted using automated systems. The SLS × date interaction on LW and ADG demonstrated that the effect of this reproductive trait on LW changes varies over time, highlighting the importance of frequent data collection for this particular application. Understanding and discussing the reasons for such changes in LW and ADG was beyond the scope of the present study, and this has been the focus of other research.

Multiple measurements over time are necessary to capture data that is meaningful to producers (Gonzalez-Garcia et al., 2021). The present study demonstrated that remote LW monitoring technologies are useful to assess the effects of reproductive factors on LW such as the number of lambs conceived. It is also important to note that differences in LW and ADG between single and twin bearing ewes were not consistent in both years, which could be due to numerous factors such

as environmental (weather and nutrition), animal (age), and management factors. The reasons for such inconsistencies between years are not clear and beyond the scope of the present study.

However, these findings suggest that remote prediction of SLS from LW may be challenging due to numerous factors affecting LW. In addition, these results demonstrate that the use of remotely collected LW data to identify potential factors responsible for the observed variations in LW may need considering information beyond SLS such as forage quality and quantity, environmental factors, and animal characteristics including genetics, age, and disease.

4.7 Conclusion

The present study successfully collected liveweight data on 315 mixed-aged Poll Dorset ewes over two lactations (1 in 2021 and 1 in 2022) using a WOW platform. This is the first known study in scientific literature with an extended monitoring period and large sample of commercially bred ewes from late pregnancy through to lactation. The study demonstrated the use of a precision livestock technology applicable to commercial sheep enterprises that provided critical information to improve the precision of managing liveweight for improved productivity.

The successful use of remotely collected liveweight for applications in reproductive management was demonstrated and could extend to further research in other applications such as disease detection and management, genetic evaluation and improvement, amongst others. Increasing societal concern for the quality of life of livestock has placed greater responsibility on farmers and livestock supply chains to prove that animals' physical and mental needs are met.

Further research into the use of WOW in extensive sheep operations is recommended, especially with increased use of satellite communications technology in remote properties. Furthermore, further research is encouraged to further understand, prevent, and detect ewe and lamb mortality using remote weighing systems.

4.8 Funding

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4.9 Data Availability Statement

Data available on request from L.A.G. due to restrictions.

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4.11 Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data or in the writing of the manuscript.

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Chapter 5

Remote monitoring of liveweight and growth rate of Poll Dorset lambs from birth to weaning under grazing conditions.

5.1 Abstract

Liveweight (LW) and average daily gain (ADG) of lambs are critical indicators of productivity in grazing sheep systems, and continuous monitoring of LW supports data-driven management to reach their genetic potential. The objective of the present study was to evaluate an automated in-paddock walk-over-weighing system (WOW) that measured the LW in mixed sex Poll Dorset lambs under commercial grazing conditions. The data collected across 3 years was then used to assess the effect of litter size at weaning (WLS) on LW and ADG. A total of 1,213 artificially conceived, mixed-sex Poll Dorset lambs were included in the initial analysis, with data refinement reducing the final dataset to 830 lambs. Lambs traversed an automated WOW platform to access an attractant, with each passage recording animal identification, date, time, and LW; data was subsequently refined to exclude records from animals that did not progress consistently through the system or failed to meet predefined data validation standards. Access to minerals or water was used as an attractant to encourage platform use. Lambs were born with 5.18 ± 1.06 kg on average but started using the WOW platform with an average LW of 12.49 ± 5.51 kg at 20.8 ± 17.23 days old. Liveweight at weaning was 50.36 ± 8.98 kg measured with the WOW system 118.4 ± 14.02 days old. Mixed-effects linear regression models revealed that the interaction between WLS and date affected both LW and ADG ($P < 0.05$) in 2020 and 2022, but not in 2021 ($P > 0.05$). In 2020, triplet lambs were lightest ($P < 0.05$), but LW was no different between single and twin lambs ($P > 0.05$). In contrast, single lambs in 2022 were heavier than twin and triplet lambs ($P < 0.05$) but LW was similar between twin and triplet lambs ($P > 0.05$). Remote and automated weighing of lambs at foot is possible under

commercial grazing conditions and the walk-over-weighing technology is useful to monitor and manage lamb performance. Further research is needed to determine the potential of the technology to manipulate liveweight trajectory and reach market specifications in a precise manner.

Keywords: liveweight, average daily gain, walk over weighing.

5.2 Introduction

Poll Dorset lambs are raised for meat production and therefore traits such as LW, ADG, and meat quality are critical to maximise the value and productivity of each animal (Moyes et al., 2025). As a productivity marker used by lamb producers, weaned litter size (WLS), is a direct measure of the number of lambs that survive to weaning (Bromley et al., 2001). WLS is an essential component of total litter weight weaned (TLWW), as increases in the number of lambs successfully raised to weaning directly contribute to heavier total litter weights. Earlier research concluded that weaned litter size is closely linked to a higher lambing percentage, which represents the number of lambs weaned per 100 ewes joined—a key benchmark in commercial operations (Hinch & Brien., 2013; Wright, 2020)

Therefore, the preweaning period of lambs is critical for growth, and it is best monitored through liveweight (LW) measurements (Gascoigne & Lovatt, 2015; Herath et al., 2022; Ptáček et al., 2015). The collection of early life LW data is often impractical in grazing systems (Webb, 1963; Ørskov et al., 1976). The movement of young (unweaned) livestock through a static enclosed weighing platform to capture the animal for LW assessment can negatively impact farm productivity, carcass quality (e.g., bruising), and result in loss of body fluids due to stress (Grandin, 1983; Preston, 2021). Wishart et al. (2015) observed that unweaned lambs lost an average of 0.65 kg of LW when held in sheep yards for weighing over a period of 4.72 hours.

In sheep, LW can be used to manage the variability in individual animal performance and flock or mob performance, providing unique data on growth patterns (Leroux et al., 2023). Precision livestock farming (PLF) technologies such as walk-over-weighing (WOW) systems and electronic identification (EID) tags, have the potential to address the challenge of weighing individual lambs from birth without the need for disruptive yarding or handling (Webb, 1963). The WOW technology generates data that can be analysed using predetermined algorithms to estimate LW and ADG in cattle (González et al., 2014). However, this technology has not been evaluated in lambs at foot to the authors best knowledge.

Purpose-built WOW systems for sheep use attractants, such as water or mineral supplements, to record individual LW, EID, and timestamps as animals pass through (Brown et al., 2014; González-García et al., 2018, Bates et al., 2023). Currently the WOW system remains the only suitable platform for extensive agricultural systems to measure LW and as such, provide valuable insights into growth patterns while minimizing the negative impacts of handling (Brown et al., 2015; Wishart et al., 2015).

The present research builds on previous WOW trials by (Brown et al., 2014; González et al., 2014; González-García et al., 2018). In addition, there is no current scientific literature on WOW systems of lambs from birth to weaning, particularly those involving a commercially representative number of lambs. The objectives of the present study were a) to collect and analyse LW and ADG of artificially conceived Poll Dorset lambs from birth to weaning at approximately 4 months of age using a WOW system under commercial grazing conditions, and b) to assess differences in LW and ADG according to WLS (single, twin, and triplet) from artificially conceived lambs.

Our hypothesis is that WOW technology enables remote monitoring of LW changes in Poll Dorset lambs, and such changes are dependent on WLS and date in a commercial grazing context.

5.3 Material and Methods

All experimental procedures were approved by the institutional Animal Ethics Committee of The University of Sydney (Approval 2020/1730 and 2016/983). The study was conducted in the Central Tablelands of New South Wales, Australia, within 40 km of the township of Orange (-33.283577 latitude, 149.101273 longitude). A total of 1213 artificially conceived Poll Dorset mixed-sex lambs were involved in the trial throughout the lambing and lactation periods from 1 of May to 8 August in each year 2020, 2021, and 2022. All lambs involved in the trial were fitted with a unique EID (Shearwell Australia Pty Ltd; Bendigo, Victoria 3550 Australia) within 6 hours of being born. Pregnancy diagnosis and estimation of joining dates were conducted via transabdominal ultrasonography at 70- and 98-days post-artificial insemination (AI). The pregnant ewe flock conceived lambs from both AI and natural joining. However, the present study focused exclusively on AI lambs confirmed by foetal size and count during ultrasound assessment.

Lambing started on May 1 and finished on May 17, and weaning was on 7 September for all years. A large group of ewes were split up into 3 lambing groups three weeks prior to lambing start date. This grouping was done by scanned litter size and placed into paddocks accordingly. Single and twin bearing ewes used the WOW system since late pregnancy but the triplet bearing ewes, and their lambs were managed in a different group, and they were introduced to the WOW system approximately 45 days after the start of lambing due to routine management practices of the collaborating property.

The overall mean birth weight across all litter sizes remained relatively stable over the three years (Table 5.1).

The study area is situated in a temperate zone characterized by warm summers and cool winters of New South Wales, Australia. The flock was managed under a rotational grazing system across 11 paddocks encompassing 178 hectares. Paddock sizes ranged from 8 to 40 hectares and were predominantly seeded with vetch (*Vicia sp.*), ryegrass (*Lolium perenne*), subterranean clover (*Trifolium subterraneum*), phalaris (*Phalaris canariensis*), and lucerne (*Medicago sativa*). Early lambing paddocks incorporated oats (*Avena sativa*), native pasture, and lucerne, whereas paddocks designated for mid-to-late lactation were primarily sown with subterranean clover, lucerne, ryegrass, and phalaris.

A commercially available loose, molasses-based granular lick feed (NUTRI-mins Ewe and Lamb; Advanced Animal Nutrition Pty Ltd, Forbes, New South Wales, Australia) was utilized as a dietary supplement. The formulation provided vitamins (Vitamin A: 0.250 MIU, Vitamin D: 0.05 MIU, and Vitamin E: 0.750 g/kg) and trace elements including cobalt (0.08 g/kg), iodine (0.03 g/kg), and selenium (0.01 g/kg). Additionally, the supplement contributed other minerals including potassium (0.2%), iron (2.5 g/kg), magnesium (15%), manganese (4 g/kg), sulphur (0.3%), zinc (3 g/kg), salt (30%), phosphorus (4.8%), and calcium (18%), with molasses comprising the remaining balance.

Statistical Analysis

The processing of the raw data to estimate LW and ADG were previously described by Gonzalez et al. (2014). Database development and statistical analyses were conducted using RStudio software (R Core Team, 2023).

From the initial cohort of 1,213 lambs conceived through AI, selection criteria were applied to include only those individuals that had valid LW data collected over a period exceeding 50 days and with a minimum of five recorded weight measurements. Variables were checked for normality through histograms. Separate datasets were prepared and analysed for each year.

Linear mixed-effects models were used to examine lamb LW and ADG trajectories from birth to weaning. Lamb identification was included as a random effect to account for repeated measures, and fixed effects included weaned litter size (WLS), date, and their interaction.

5.4 Results

Lambs began traversing the WOW system shortly after the onset of lambing, which commenced on the 1st of May each year. Single and twin born lambs were introduced to the WOW platform soon after birth, with the earliest recorded entry occurring within the first week of lambing (Table 5.2). In contrast, triplet-born lambs were integrated into the WOW system approximately 45 days after the start of lambing. This delay was due to their birth in a separate management cohort, resulting in later system access and higher mean age at first WOW event—particularly evident in 2022, where the mean age at first WOW was 38.1 days compared to 18.1 and 11.8 days in 2020 and 2021, respectively (Figure 5.1).

Table 5. 1 Descriptive statistics for birth weight according to weaned litter size of artificially conceived Poll Dorset lambs used for remote monitoring of liveweight in the paddock.

Litter Size	n	mean	STD	median
2020				
1	109	5.78	1.174	5.88
2	222	5.08	0.940	5.13
3	36	4.05	1.016	3.98
Mean	-	5.19	1.133	4.99
2021				
1	77	5.83	1.165	5.96
2	165	4.97	0.855	4.94
3	26	4.33	0.729	4.44
Mean	-	5.16	1.054	5.11
2022				
1	60	5.84	0.934	5.99
2	125	4.92	0.681	4.92
3	10	4.23	0.606	4.23
Mean	-	5.17	0.899	5.02

n – number of animals in analysis; STD – standard deviation

Table 5.2 provides a comparative summary of lamb birth dates, entry into WOW systems, and associated LW measurements across three lambing cohorts from 2020 to 2022. The range of birth dates was consistent across years, typically occurring in early to mid-May, with the earliest lambing recorded on 30 April 2021 and the latest on 17 May 2020. Entry into the WOW system varied by year, with lambs in 2022 entering substantially later on average (14 June) compared to 2021 and 2020 (19 May and 28 May, respectively). The final WOW measurements also followed a similar trend, with the last entries extending into early to mid-September each year. Lamb age at first WOW recording showed marked variation, averaging 38.1 days in 2022 compared to 11.8 days in 2021 and 18.1 days in 2020, reflecting delayed WOW integration in 2022. Despite these differences in timing, the duration of WOW participation remained relatively consistent, with mean age at last WOW ranging between 114 and 128 days. Liveweight at first WOW measurement was lowest in 2021 (mean 9.8 kg) and highest in 2022 (mean 17.1 kg), aligning with the older age at initial entry in that cohort. Maximum first weights increased across years, indicating overall improvements in early growth.

Table 5. 2 Summary of birth dates, walk-over weighing entry, and liveweight measurements for lambs across 2020–2022 lambing cohorts.

Item	2020	2021	2022
Date of Birth			
Minimum	3/05/2020	30/04/2021	2/05/2022
Mean	10/05/2020	7/05/2021	7/05/2022
Maximum	17/05/2020	16/05/2021	14/05/2022
First WOW date			
Minimum	8/05/2020	9/05/2021	9/05/2022
Mean	28/05/2020	19/05/2021	14/06/2022
Maximum	17/07/2020	28/06/2021	22/07/2022
Last WOW date			
Minimum	6/07/2020	8/07/2021	21/07/2022
Mean	1/09/2020	1/09/2021	12/09/2022
Maximum	5/09/2020	30/09/2021	18/09/2022
Age at First WOW, days			
Minimum	0	1	0
Mean	18.1	11.8	38.1
Maximum	69	51	76
Age at Last WOW, days			
Minimum	62	62	73
Mean	114	117	128
Maximum	123	150	139
First WOW weight, kg			
Minimum	5.3	5.1	5.7
Mean	12.0	9.8	17.1
Maximum	32.0	24.1	37.0

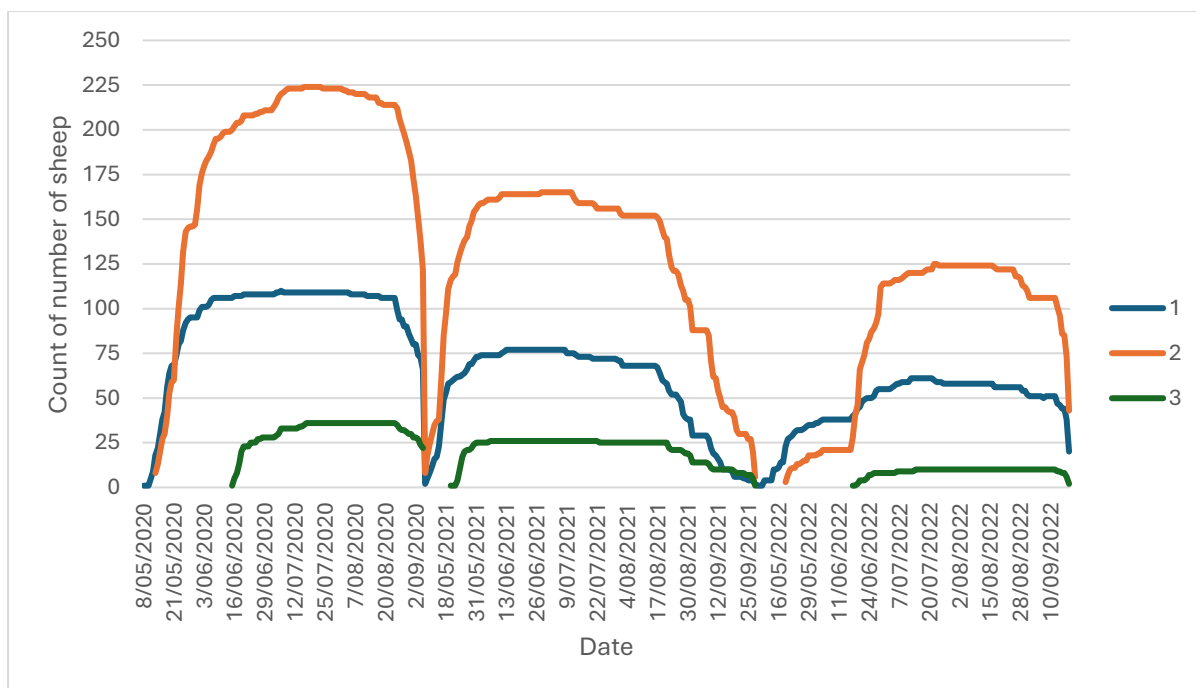


Figure 5.1 Number of lambs with data in the final walk-over-weighing dataset after deleting outliers.

Statistical analysis results disclose that the effects of weaned litter size, date, and their interaction on LW and ADG varied across the years 2020, 2021, and 2022 (Table 6.3). For LW, WLS was a significant factor in 2020 and 2021 as indicated by high F-values, but not in 2022. Date consistently influenced LW outcomes across all three years with particularly large F-values indicating a dominant influence of time-related factors. While the interaction between WLS and date was significant in 2020 and 2022 as shown by moderate F-values. In terms of ADG, the effect of WLS was not significant in 2020 but became progressively more influential in 2021 and 2022. Date remained a significant factor across all years for ADG. The interaction between WLS and date was also significant in 2020 and 2022, but not in 2021.

Table 5. 3: Statistical analysis of weaned litter size and date effects on lamb liveweight and growth performance from 2020 to 2022

	2020		2021		2022	
	F-value	P-value	F value	P-value	F value	P-value
Predicted Liveweight, kg/hd						
Weaned litter size	29.2	<0.001	9.7	<0.001	0.3	0.723
Date	2236.5	0.001	1091.5	0.001	39.1	<0.001
Weaned litter size × Date	2.1	<0.001	0.9	0.942	1.2	0.013
Average Daily Gain, kg/d						
Weaned litter size	1.8	0.169	2.0	0.019	1.3	< 0.001
Date	12.1	<0.001	8.0	<0.001	0.9	< 0.001
Weaned litter size × Date	2.4	<0.001	0.5	0.086	2.7	<0.001

Figures 5.1a, 5.2a, and 5.3a display the LW trajectories over 13 weeks for single, twin, and triplet-weaned lambs in 2020, 2021, and 2022, respectively. The triplet lambs were raised as a separate cohort until approximately 45 days after the start of lambing, so LW and ADG is available from then only. In 2020, LW trajectories showed a greater separation between litter sizes compared to 2021, which had a non-significant WLS × date interaction ($P > 0.05$). The difference in LW between single and triplet lambs at the end of the period was 4.1, 3.9, and 5.2 kg in 2020, 2021, and 2022 (Figure 5.1 to 5.3).

Figures 5.2b, 5.3b, and 5.4b present ADG outcomes for each year of the study. In 2020, single and triplet lambs reached the fastest ADG of 0.49 kg/d at the beginning of July (2 months after start of lambing) whereas twin lambs reached the fastest ADG of 0.47 at the end of July and August (3 months after start of lambing). Findings were similar in 2021 with fastest ADG in July for all groups, although there was no significant WLS × date interaction.

The ADG trajectory was more variable in 2022 compared to 2020 and 2021, particularly for twins and triplets. However, twins recovered faster and achieved the highest ADG at the end of the trial, compared to both singles and triplets ($P < 0.05$) whereas single lambs maintained the most consistent ADG trajectory.

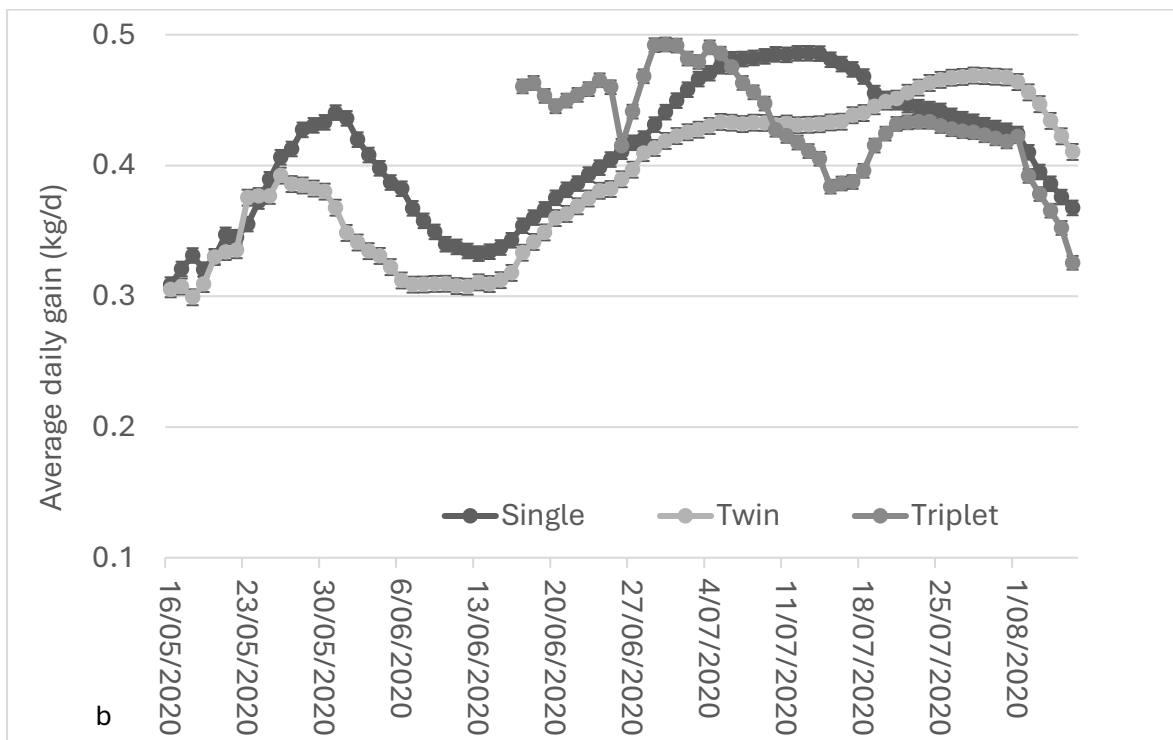
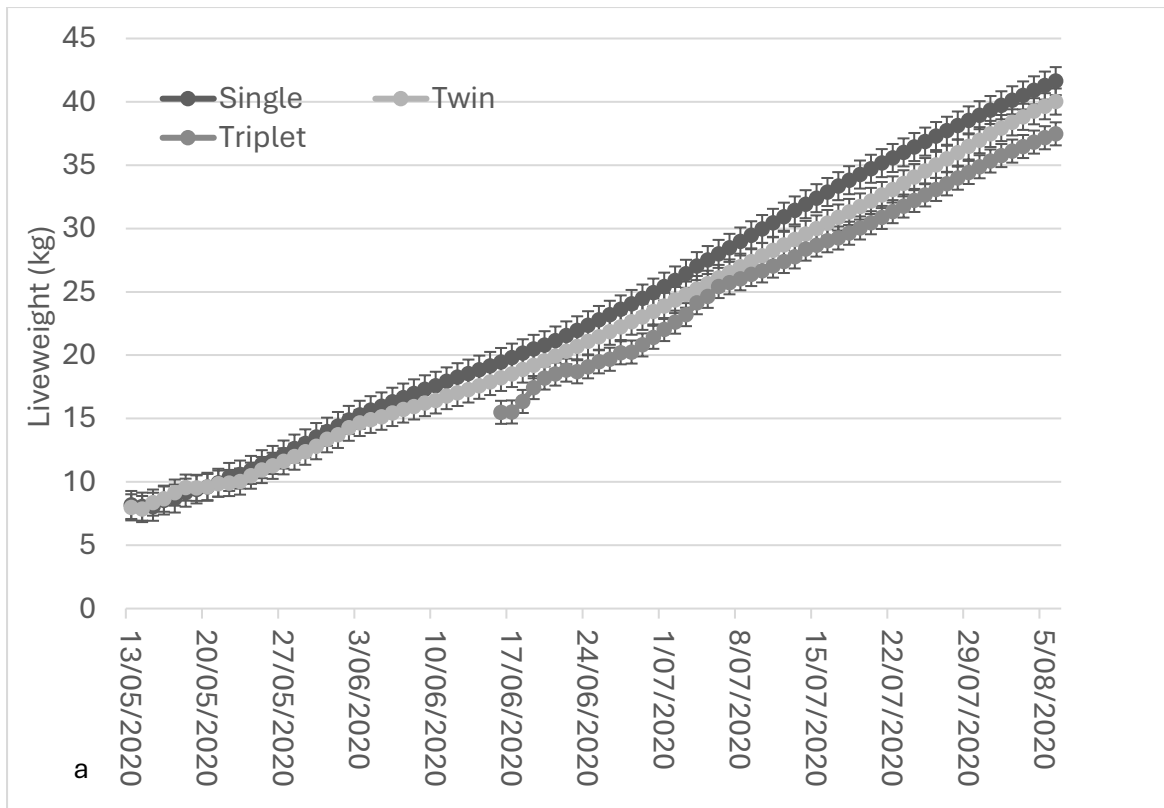


Figure 5.2 Liveweight (a) and average daily gain (b) of Poll Dorset lambs measured using an automated walk-over weighing system in 2020.

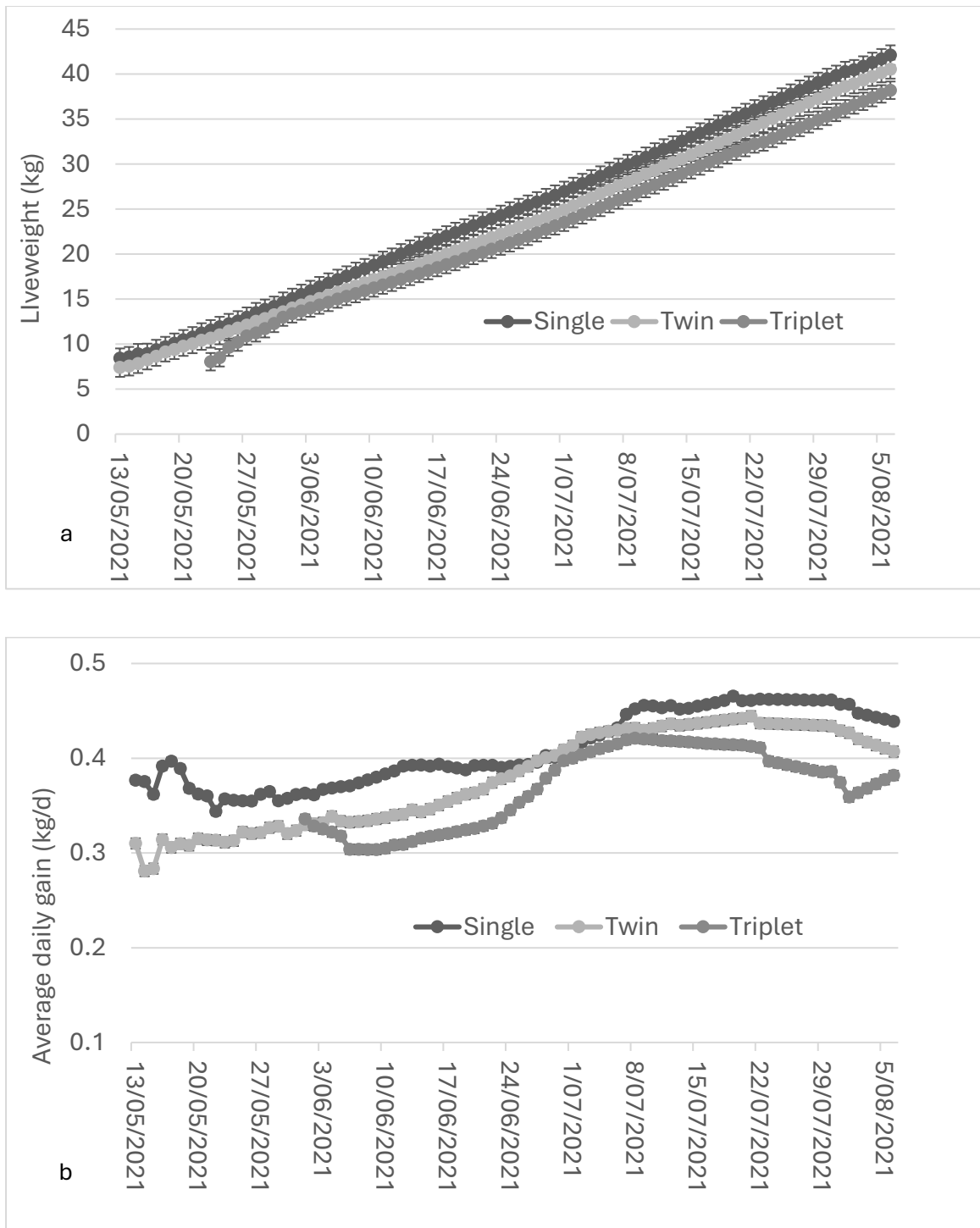


Figure 5.3 Liveweight (a) and average daily gain (b) of Poll Dorset lambs using an automated walkover weighing system in 2021.

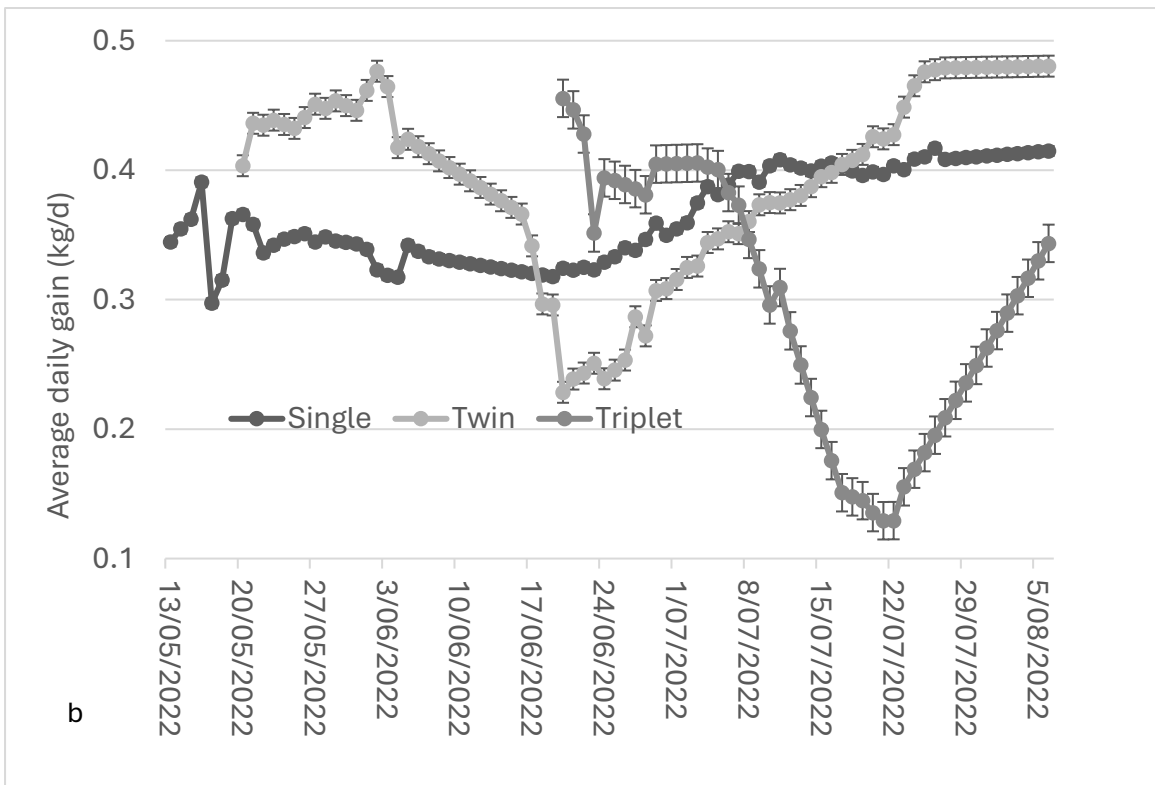
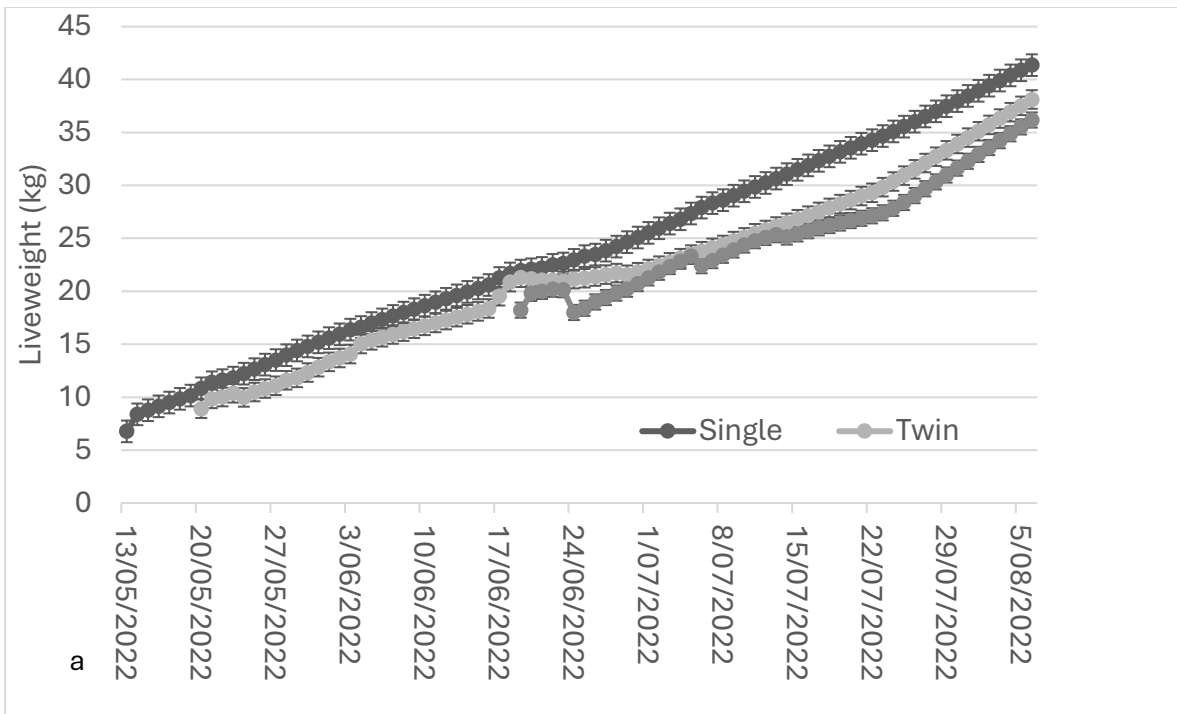


Figure 5.4 Liveweight (a) and average daily gain (b) of Poll Dorset lambs using an automated walk-over weighing system in 2022.

5.5 Discussion

Among the tools with potential for commercial application is the integration of electronic identification (EID) ear tags with in-paddock automatic WOW platforms (Brown et al., 2012; Brown et al., 2015; Aquilani et al., 2022). The LW and ADG results shown in the present study offer insights into animals' responses to their environment, management, and genetic potential of the animals, and this information can be used for supporting management decisions that can enhance productivity and minimise negative impacts, ultimately influencing overall welfare outcomes (Thompson et al., 2011; Schillings et al., 2021; Leroux et al., 2021).

It is well recognized within livestock production that variations in LW exist within flocks and among mobs of paddock-grazed animals (Thompson et al., 2021; Ahmad et al.,2022). The adoption of remote monitoring technologies, such as WOW systems, is advancing as part of PLF innovations, offering significant opportunities for managing sheep productivity (Bates et al., 2023).

Some lambs started using the WOW system since the first day of life in the present study albeit this requires frequent rounds for tagging lambs by farm staff soon after birth. However, it is important to point out that on average, lambs started using the WOW system at approximately 12 days old and 9.8 kg LW in 2021, and 38 days old and 17.1 kg in 2022. These results suggest that collecting LW data during the first days of life may be challenging, which could become a hindrance for some applications such as monitoring lamb mortality because these are most prevalent during the first 3 days of life (Shiels et al, 2025). Nevertheless, the integration of WOW technology in lambing flocks has the potential to become a valuable tool for monitoring and managing lamb performance to weaning. It is important to note that the average age at which lambs started to use the WOW system in the current study was late because triplet lambs were introduced to the WOW at an older age due to farm routine management and logistical challenges with monitoring multiple cohorts of ewes in different paddocks.

The WLS × date interaction had a significant impact on LW and ADG in 2020 and 2022 indicating that the trajectories of LW and ADG were dependent on WLS. These findings have previously been reported from static weighing of lambs (Brown et al., 2012; Gonzalez-Garcia et al., 2018), however the present study seems to be the first to demonstrate that the effect of WLS on both LW and ADG over time can be detected with remote automatic weighing of lambs in the paddock. The reason for WLS × date interaction to be insignificant in 2021 is unclear and it was beyond the scope of the present study, although it suggests that factors other than WLS affect the growth trajectories of lambs in addition to WLS such as nutritional, environmental or management conditions.

The use of the WOW system to collect data from commercially grazed lambs in the present study, from birth to weaning, demonstrated the feasibility of doing so in young sheep. The findings presented in the present study offer novel insights that complement existing research (González-García et al., 2018; González et al., 2014) and highlights the application of the WOW as a PLF tool.

Additionally, the present study contributes new knowledge on the effects of date as a proxy for age and litter size as key factors influencing developmental and physiological processes in sheep.

These technologies could support timely and informed management decisions, optimize nutrition, and track health and welfare. Despite these advancements, the absence of real-time decision support tools limits producers' ability to fully leverage on-farm data for financial and management decisions. Addressing this gap can empower producers to identify and prioritize critical on-farm factors and foster a deeper understanding of animal responses to environmental changes (Brown et al., 2012; Brown et al., 2015; Thompson et al., 2011; Wishart et al., 2017; González-García et al., 2018; Schillings et al., 2021; Aquilani et al., 2022).

The adoption of remote monitoring technologies, including WOW systems, for managing health and welfare of sheep flocks is progressing alongside advancements in PLF technologies (Brown et al., 2015). However, the absence of decision support tools that enable real-time evaluation of different scenarios using on-farm data limits producers' ability to make timely management and financial

decisions. There is a significant opportunity for producers utilizing PLF tools, such as WOW technologies, to identify, quantify, and prioritize on-farm factors that increase short- and long-term productivity and sustainability.

Investment in PLF technologies across various production systems can enhance understanding of both the technologies themselves and the interactions between animals and their environment, including the effects on growth and development (Morgan-Davies et al., 2015; Wishart et al., 2017; González-García et al., 2018). A key benefit, both in the short and long term, is that the WOW system can be used to understand the influence of environmental changes on liveweight, which are linked to productivity.

5.6 Conclusion

The present study demonstrated that WOW can provide LW data for detailed analysis of temporal trends to assist with the challenges of managing lambs under commercial grazing conditions. It demonstrated that lambs can be successfully monitored remotely while at foot with their dams under grazing conditions from birth to weaning in large flocks. Accordingly, automated LW monitoring should be implemented as early as possible before the start of lambing to enable the timely detection of neonatal mortality under commercial grazing conditions. Early initiation of monitoring will also provide more accurate and biologically relevant insights into early life growth trajectories, survival outcomes, and the key factors influencing lamb viability. This presents unique real-time information to improve the precision of management decisions throughout lactation. In addition, as the significant interaction between weaned litter size and date in lamb production systems further demonstrates that important biological factors are reflected in the remotely collected LW data offering further information for management decisions. The observed patterns suggest that WOW systems can detect both date or age-related effects and biological differences due to litter size. Future research should focus on identifying the underlying causes of the year-to-year and day-to-day variations observed in LW and ADG of the present study, to develop more

robust and adaptive management strategies. The use of emerging agricultural technologies for remote monitoring of liveweight over time could present opportunities to manage productivity and welfare through factors such as nutrition, health, and genetic selection. This area holds potential for developing tools that predict animal profit, health, and welfare status.

To our knowledge, this is the first published study to report the use of automated walk-over-weighing technology of lambs encompassing birth, rearing, and longitudinal LW monitoring under commercial grazing conditions.

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5.8 Data Availability Statement

Data available on request from L.A.G. due to restrictions.

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5.10 Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript.

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Chapter 6

Factors affecting survival in Poll Dorset lambs.

6.1 Abstract

Lamb mortality remains a significant production and welfare challenge in Australian sheep systems, with pre-weaning survival rates typically averaging 75–80%. Lamb survival is influenced by complex interactions among genetic, physiological, and management factors, necessitating multivariate analyses to identify key predictors. This study investigated determinants of lamb survival in Poll Dorset lambs, including birth weight (BWT), gestation length (GL), lambing ease (LE), maternal wool length (MWL; shorn vs. crutched), gender, litter size (LS), ewe age, temperament, and udder score. The utility of walk-over-weighing (WOW) technology to support lamb survival management was also evaluated using ewe liveweight (LW) recorded during the 7 days pre- and post-lambing.

A dataset of 852 Poll Dorset lambs born via artificial insemination across two lambing seasons (2020–2021) was analysed using binomial generalized linear models with backward stepwise selection. Survival was higher in single- and twin-born lambs compared with triplets ($P < 0.05$), and in unassisted compared with assisted parturitions ($P < 0.05$). BWT had a strong quadratic effect ($P < 0.001$), with both low and high BWT associated with reduced survival. Lambing ease also affected survival ($P < 0.001$), confirming parturition difficulty as a major risk factor. Other factors, including ewe age, MWL, and udder score had non-significant effects.

Ewe pre-lambing LW measured using WOW technology was associated with lamb survival (quadratic: $P = 0.037$), particularly in triplet-bearing ewes, where both low and high LW were associated with reduced survival ($P < 0.05$). Ewe post-lambing LW and average daily gain did not affect survival ($P > 0.10$). When BWT was included in place of LS, the effect of ewe pre-lambing LW was reduced ($P = 0.058$), indicating mediation through BWT. These findings highlight birth weight and lambing ease as primary determinants of survival and demonstrate the potential of WOW

technology to support ewe pre-lambing LW and lamb birth weight management and improve lamb survival under commercial grazing conditions.

Key words: birth weight, lambing ease, gestation length, lamb survival

6.2 Introduction

Lamb survival continues to be raised within the Australian sheep industry as a significant production and animal welfare concern (Dwyer, 2008; Kopp et al., 2020). Lamb survival results from a complex interaction between direct and maternal genetic and non-genetic factors that influence gestation and parturition outcomes (Bunter et al., 2023). Although substantial variation in lamb survival is observed by producers across flocks, regions, and years, pre-weaning lamb survival typically averages between 75 and 80% in Australia (Hinch & Brien, 2014).

Litter size has a huge influence on both phenotypic outcomes and genetic correlations (Kelly et al., 2017), so it is essential to account for litter size when evaluating and selecting traits such as lamb survival, BWT, and LE. Failure to consider these interactions may obscure important sources of variation and limit the effectiveness of breeding programs aimed at improving perinatal lamb survival (Hatcher et al., 2010). Therefore, a more nuanced understanding of the effect of maternal and litter-related factors on lamb survival is critical for developing more targeted and efficient selection and management strategies. Maternal influences exerted by the ewe are fundamental to lamb survival, encompassing contributions to in-utero development (such as BWT), and assistance during parturition measured through LE scores (Dwyer, 2008; Bunter et al., 2017). Changes in genetic traits such as BWT, GL, and LE have been observed when these traits are analysed separately according to litter size at birth (Li & Brown, 2016; Bunter et al., 2017), as have shifts in the genetic traits associated with lamb survival (Hatcher et al., 2010; Kelly et al., 2017). These findings suggest that litter size at birth can substantially influence the genetic architecture of key reproductive and survival traits, a pattern consistent with the observations reported by Refshauge et al. (2015).

LE is a key factor for both animal welfare (Dwyer, 2008) and the profitability of sheep farms, affecting labour costs, ewe mortality, and lamb weaning rates. BWT and GL are correlated traits that impact LE and are used to improve genetic evaluation of LE (Brown, 2007; Hatcher et al., 2009; Li & Brown, 2016), given their biological relevance to the birth process. The incidence of dystocia due to increased BW in large lambs tends to decrease with larger LS (Refshauge et al., 2015), but lambing assistance may remain necessary owing to obstructive difficulties, maternal fatigue, or health conditions such as hypocalcaemia.

Bunter et al. (2017) found that the association between LS and BWT was linear, but other relationships were non-linear, suggesting that linear models may not fully predict lamb survival. Despite this, linear models are effective for genetic improvement of categorical traits (Bunter et al., 2017). Recent findings indicate a significant genetic correlation between lamb survival and BWT, with estimates ranging from -0.63 to -0.81 for single-born lambs, and from -0.00 to -0.23 when twins are included (Bunter et al., 2023). These relationships offer valuable insights for the refinement of breeding strategies aimed at enhancing lamb survival. The strong negative genetic correlation observed in single-born lambs suggests that as birth weight increases beyond an optimal range, survival may decline—likely due to increased risk of dystocia and associated perinatal complications. In contrast, the weaker correlations observed when twins are included may reflect the more complex interplay between foetal growth, placental efficiency, and maternal capacity in multiple births.

The relationship between BWT and lamb survival follows a quadratic pattern as reported by Atkins (1980), Knight et al. (1988), and Oldham et al. (2011). Survival rates in Merino sheep increased with BWT, peaking at approximately 4.5 kg but lambs born below this threshold exhibited reduced viability (Oldham et al., 2011). However, in single-born Merino lambs, survival declined when BWT exceeded 6.5 kg, suggesting an increased incidence of dystocia and perinatal complications associated with heavier lambs (Oldham et al., 2011). Twin-born Merino lambs consistently exhibited

lower survival rates across all BWT classes, reflecting intrauterine growth restriction and heightened vulnerability postpartum (Oldham et al., 2011). This research is contradicted by the recent findings of Bunter et al. (2023), who concluded that lamb survival is positively correlated with BWT, but negatively associated with GL and LE scores.

Earlier research by Dwyer & Bünger (2012) into specific United Kingdom bred sheep demonstrated that terminal sire breeds, specifically Texel and Suffolk, experienced significantly higher levels of dystocia and reduced lamb vigour compared to Scottish Blackface and crossbred maternal lines. This study also found that 25.1% of lambs were incorrectly presented at birth, with Suffolk and Texel lambs significantly more likely to be misrepresented than Scottish Blackface and Mule-cross breeds. Dorset Horn ewes tended to have a small pelvic area and a high incidence of dystocia (Fogerty & Thompson, 1974). Normally presented lambs were more likely to be delivered without assistance, while misrepresented lambs often required major or veterinary assistance (Fogerty and Thompson, 1974). Despite this extensive information in Merino, more information is lacking in sheep meat breeds such as Poll Dorset.

The economic and genetic importance of lamb survival in Australian Poll Dorset flocks was demonstrated by Hall et al. (1994), who reported that net reproductive rate in Dorset breeds is pivotal for selection intensity, breeding program design, flock profitability, and the flow of genetic improvement into the lamb industry. Their study found that lamb deaths were primarily attributed to dystocia (53%), starvation–mismothering–exposure (SME; 23%), and other causes (24%).

Interestingly, stud, ewe age, year, and parity did not significantly influence the proportion of deaths due to each cause. Instead, LS had a highly significant effect ($P < 0.001$) on both dystocia and SME, while ewe LW at joining also exerted a significant influence ($P < 0.001$). Although overall lamb survival was not directly affected by either LS or ewe LW, the proportion of deaths due to SME increased sharply in multiple-born lambs as ewe LW rose. Scales et al. (1986) demonstrated that ewe ADG during the final six weeks of pregnancy was positively associated with lamb BW in both single and twin lambs ($P < 0.05$), with approximately 10 kg of maternal gain resulting in a 0.5 kg increase in

BWT. Increased BWT may enhance lamb viability through improved thermoregulation and vigour but also increases dystocia risk, particularly in terminal sire breeds whilst mortality of single-born lambs was not affected by ewe ADG or LW at lambing (Scales et al., 1986). This suggests that late pregnancy feeding of ewes may support lactation. In contrast, increased nutrition in multiple-bearing ewes reduced lamb mortality. Scales et al. (1986) also identified a threshold effect, where mortality increased sharply when ewe pre-lambing LW fell below 40 kg, while mortality remained relatively stable between 40 and 80 kg, highlighting the importance of adequate maternal body condition during late gestation. Moreover, ewe LW at the start of lambing had little effect on the proportion of ewes requiring assistance, emphasising that dystocia risk is more strongly influenced by foetal size and presentation than by absolute ewe weight alone (Scales et al., 1986). These results parallel the findings of Hall et al. (1994), reinforcing the conclusion that ewe condition influences survival indirectly by altering the distribution of causes of death rather than overall survival probability. The provision of continuous LW records through WOW technologies offers a distinct advantage over the static and retrospective information obtained from conventional weighing methods. By capturing fine-scale changes in ewe LW across key reproductive stages, WOW enables the detection of trend that would otherwise remain unnoticed. This capability may allow for the implementation of earlier and more precise management interventions, thereby reducing reproductive inefficiencies and enhancing lamb survival outcomes.

The present study aimed to identify and assess key biological and management factors influencing lamb survival in Poll Dorset sheep. The central hypothesis of this study was that lamb survival is significantly influenced by various factors (as well as their interactions), including BWT, GL, LE, gender, MWL, LS, and ewe pre-lambing LW.

6.3 Material and Methods

All experimental procedures were approved by the Institutional Animal Ethics Committee of the University of Sydney (Approval 2020/1730 and 2016/983). The study was conducted in the Central Tablelands region of New South Wales, Australia.

This study utilized a lamb dataset from 2 years (n 554 in 2020; n= 656 in 2021) containing all individual records of lambs born from artificial insemination (AI) and natural joining over two winter lambing periods. Out of the total 1,210 lambs born from both AI and natural joining, 852 Poll Dorset lambs conceived via AI were selected for the present analysis. This selection process ensured a consistent management background for the animals, minimizing potential confounding factors such as variations in GL and MWL, which could arise from natural mating where the conception date is unknown.

The ewes' pregnancies occurred via AI in mid-December the year prior and was confirmed by ultrasound assessment including foetal aging up to 2 months pre-birth. Although the AI technician and the ultrasound assessor were distinct individuals, both procedures were performed by the same technician for both years.

The trial recorded three distinct litter sizes among lambs: singletons (litter size = 1) accounted for 20.9% of lambs, twins (litter size = 2; 57.1% of lambs) were the most prevalent, and triplets (litter size = 3) represented 22.0% of lambs (Table 6.1). The overall sex distribution was approximately equal across all litter sizes, with 49.6% ewe lambs and 50.4% ram lambs observed (Table 6.1). Within each litter size category, the proportions of ewe and ram lambs remained consistent, with ewe lambs comprising 19.1%, 56.7%, and 24.1% of single, twin, and triplet litters, respectively, and ram lambs 22.1%, 57.6%, and 20.3% of each respective litter size (Table 6.1).

Lamb survival outcomes during the trial period indicated a total mortality rate of 14.9% (Table 6.1).

Mortality was most frequently observed among triplet litters (26.5%), followed by twins (12.1%) and singletons (10.2%; Table 6.1).

Table 6. 1. Frequency distribution of lamb survival status by litter size, sex, and maternal wool treatment, expressed as counts (n) and proportions (%).

Litter Size	Lambs					Dams		
	Total	Ewes (n, %)	Rams (n, %)	Deceased (n, %)	Alive (n, %)	Total	Shorn (n, %)	Crutched (n, %)
1	176	81 (46.0%)	95 (53.9%)	18 (10.2%)	158 (89.8%)	180	74 (41.1%)	106 (58.9%)
2	487	240 (49.3%)	247 (50.7%)	59 (12.1%)	428 (87.9%)	196	86 (43.9%)	110 (56.1%)
3	189	102 (54.0%)	87 (46.0%)	50 (26.5%)	139 (73.5%)	63	29 (46.0%)	34 (54.0%)
Total	852	423 (49.6%)	429 (50.4%)	127 (14.9%)	725 (85.1%)	439	189 (43.0%)	250 (57.0%)

* Percentages in each line refer to the total column for each litter size for lambs and dams respectively.

A total of 439 mixed aged Poll Dorset ewes (i.e. maternal mothers) were included across both lambing seasons (Table 6.1). The percentage of ewes with 2, 3-, 4-, 5-, and 6-year-old was 2.6, 14.9, 39.1, 32.5, and 10.9%, respectively. Prior to lambing, ewes were either shorn (n = 189), where ewes underwent full-body shearing, or crutched (n = 250), where wool was removed only from the breech and udder area. In 2020, ewes were shorn and crutched 58 days before the start of lambing. In contrast, the 2021 cohort was shorn and crutched 36 days before lambing was expected to commence.

On-farm data was recorded by the producers and their team at the trial site. GL was determined by calculating the interval between the artificial insemination (AI) date and the actual date of parturition. Conception was verified through ultrasound examination, with foetal aging conducted approximately 40 days prior to the expected lambing start date of May 1st. The date of lambing was recorded on the day each ewe gave birth, with lambing paddocks inspected twice daily to ensure

accurate data collection. Based on ultrasound assessments of foetal number, ewes were stratified into lambing cohorts approximately three weeks before the onset of lambing to facilitate targeted management. LS was recorded as the total number of lambs born per ewe, including both live and stillborn individuals. This information was collected concurrently with BWT measurements, ear tissue collection for DNA analysis, and ear tagging by the farm managers and their team. LE was recorded as either unassisted or assisted, with all lambs requiring human intervention during parturition recorded under the assisted category. BWT was measured using a handheld digital scale equipped with a supporting sling. The sling was securely placed around the lamb's forelegs, allowing the animal to be suspended off the ground in a natural hanging position while weight was recorded. This method ensured accurate and consistent weight measurements within 24 hours after lambing.

Temperament scoring was conducted to assess ewe behaviour and proximity tolerance, which was considered critical by the managers for both predator (human or animal) awareness and on-farm management practices such as lambing observation and ewe EID scanning post lambing. The scoring system ranged from 1 to 5 (Meat & Livestock Australia, 2019), with 1 indicating an ewe that stands in proximity to the observer and 5 indicating an ewe that is distant, disengaged, and requires the lamb to be returned to her. Specifically, a score of 1 represents an ewe standing directly next to the observer; 2 indicates a distance within 1 metre; 3, within 3 metres; 4, within 10 metres while still observing the surroundings; and 5 denotes an ewe that remains distant and unengaged. These behavioural metrics were considered crucial by the manager for assessing maternal attentiveness and response to disturbance, which are important predictors of lamb survival under extensive grazing conditions.

Udder scoring was based on the ease with which a lamb can successfully attach and suckle and visual conformation of the udder and teats. The assessment focused on symmetry, teat placement (neither too high nor too low), and teat orientation ideally pointing downward at a 45-degree angle. Teats should be of a size suitable for the lamb mouth conformation, and the udder itself should be well-

rounded and not pendulous. Scores ranged from 1 (ideal) to 5 (poor), with scores of 1–3 considered suitable for rebreeding in the subsequent year. A score of 4 reflects a misshaped udder where the lamb can still feed independently, while a score of 5 indicates the lamb required human assistance to latch. Together, temperament and udder scores are used in classing decisions to evaluate an ewe's capacity to successfully rear a lamb in the following season. Milking ability is also considered implicit during this assessment. This is similar in description to the extensive udder scoring in recent research by Richardson (2023).

Statistical Analysis

The dataset was processed and analysed in R (version 4.4.3; R Core Team, 2025) using a generalized linear model (GLM) with a binomial distribution and a logit link function to the outcome binary variable, lamb survival either alive or dead at marking to model the likelihood of survival.

A backward elimination procedure was used to develop a parsimonious model while retaining biologically relevant predictors. A threshold of $P < 0.10$ was applied to avoid excluding variables with moderate but potentially meaningful biological effects. The backwards selection of variables was performed, starting with a model containing all categorical factors (LE, LS, MWL, GEN, udder score, temperament, and ewe age), and all possible 2- and 3-way interactions and deleting higher order interactions that were not significant until the final model contained factors with $P < 0.10$. A second model was developed for lamb survival adding the linear and quadratic terms for BWT, ewe age, and GL to the model above, followed by backwards elimination of factors with $P > 0.10$ to assess the potential non-linear relationship between these covariates and survival probability.

Finally, a third model was explored to use the dams' walk-over-weighing data to predict lamb survival using the above predictors plus dam average liveweight 7 days prior to lambing, 7 days after lambing, and growth rate as linear and quadratic covariates.

6.4 Results

The analysis of deviance shows the contribution of key biological and management-related predictors to lamb survival. In the model with only categorical variables, LS and LE as main factors were significant ($P < 0.001$; Table 6.3) and udder score ($P = 0.07$) and MWL ($P = 0.08$) showed a weak tendency, but no other main factor or interactions were significant and were therefore eliminated from the model. The model showed LS and LE explained a similar amount of the variation in observed lamb survival as reflected in their similar deviance and the change of it, whereas udder score and MWL showed much smaller deviance (Table 6.2).

Table 6. 2 Effect of litter size, lambing ease, udder score, and maternal wool length on the likelihood of lamb survival.

	Df	Deviance	Residual. Df	Residual. Deviation	* $p < \chi^2$
Intercept only	-	-	843	657	-
Litter size	2	27.8	841	629	<0.001
Lambing ease	1	35.2	840	594	<0.001
Udder score	2	5.4	838	589	0.068
Maternal wool length	1	3.1	837	586	0.078

* $p < \chi^2$ = probability >Chi-Square test statistic

Single lambs had the highest survival rate but similar to twins ($P > 0.05$) and both single and twin lambs had 28.1 and 21.6% higher survival compared to triplets ($P < 0.05$; Figure 6.1). In addition, lambs born from unassisted birthing were 34.4% more likely to survive compared to lambs born from assisted lambing ($P < 0.05$; Figure 6.2). Lambs born to ewes with udder score of 2 had 9.8% greater likelihood to survive compared to lambs born to ewes with higher udder score ($P = 0.068$; Figure 6.3). The MWL showed that lambs born to ewes that were crutched had 7% lower probability to survive compared to those born to shorn ewes (72.1 ± 4.03 vs. 79.1 ± 3.52 %, respectively).

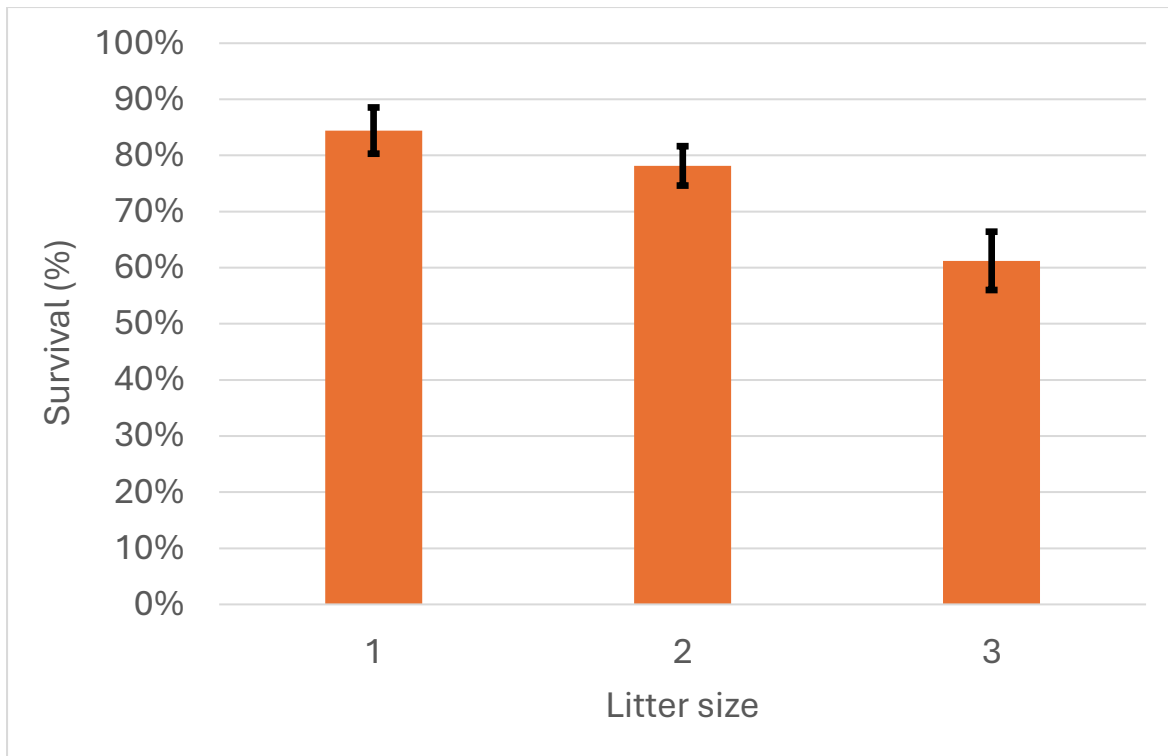


Figure 6. 1 Effect of litter size on lamb survival (%) in Poll Dorset lambs.

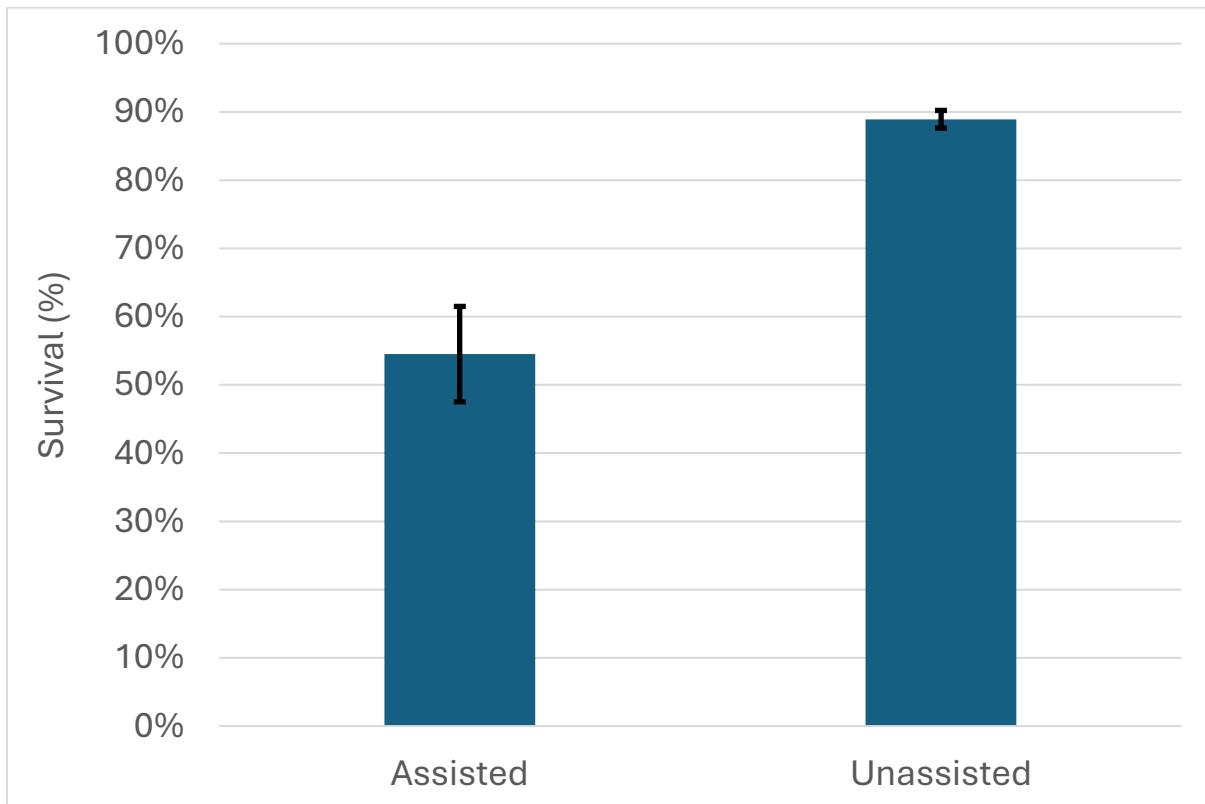


Figure 6. 2 Lamb survival (%) by birth assistance in Poll Dorset lambs.

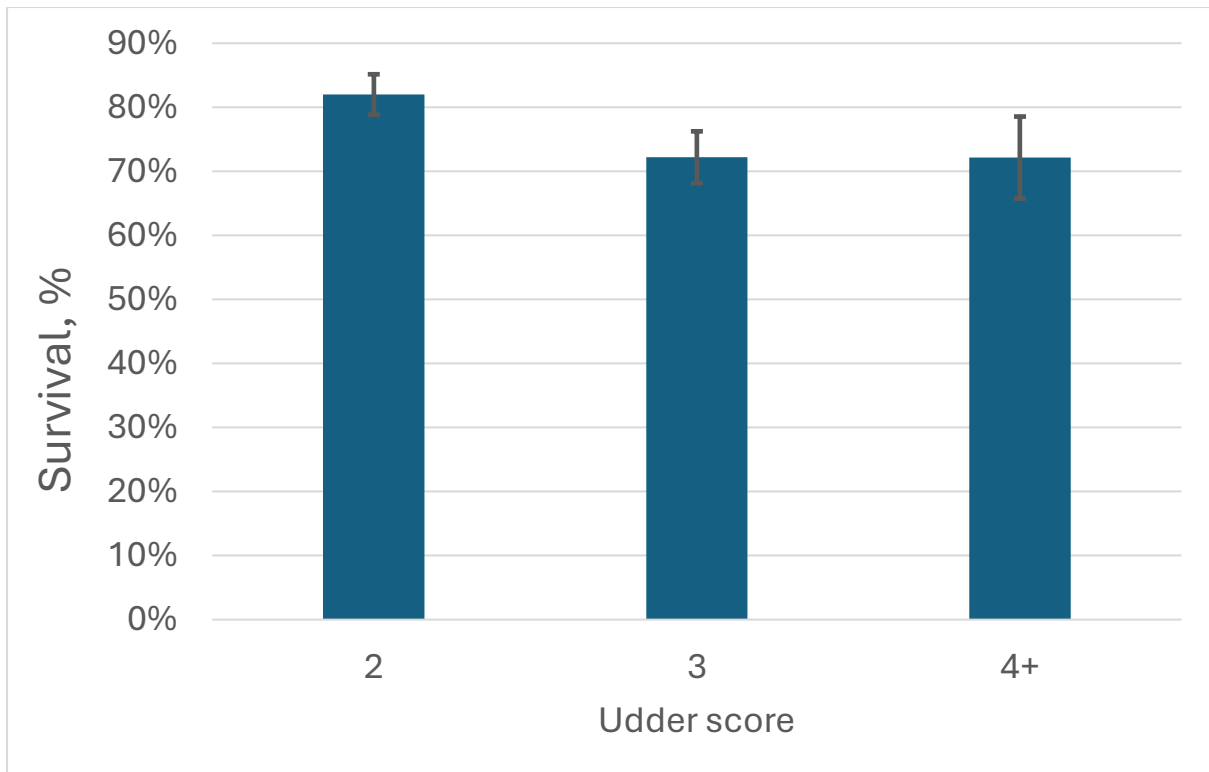


Figure 6.3 Effect of udder score on lamb survival (%) in Poll Dorset lambs.

The model containing all categorical and linear covariates showed that most main factors and interactions did not affect survival ($P > 0.05$), except for the birth weight with quadratic terms and ewe age as linear, and the categorical variables litter size, udder score, and birthing ease ($P < 0.05$; Table 6.3). Interestingly, BWT and LE explained the largest variation in lamb survival as evidenced by the deviance of each factor whereas ewe age and LS had the lowest influence on survival (Table 6.3).

Table 6. 3 Effect of birth weight, ewe age, lambing ease, udder score, and litter size on lamb survival.

Variable	Df	Deviance	Resid. Df	Resid. Dev	*p < χ^2
Intercept only			842	653	
Birth weight, kg	1	36.7	841	616	<0.001
Birth weight, kg ²	1	12.6	840	604	<0.001
Litter size	2	6.5	838	597	0.039
Lambing ease	1	42.3	837	555	<0.001
Udder score	2	11.2	835	544	0.004
Ewe Age, years	1	4.4	834	539	0.035

*p < χ^2 = probability >Chi-Square test statistic

The fitted model including both linear and categorical variables showed that only BWT (linear and quadratic), ewe age, LE, and udder score were significantly associated with lamb survival (P < 0.05; Table 6.4). Birth weight and LE were the most influential predictors, contributing substantially to the variation in survival likelihood. In contrast, LS had no significant effect (P > 0.90 Table 4.4), while ewe age and udder structure exhibited moderate but statistically meaningful associations with survival outcomes.

Table 6. 4 Parameters of a linear regression model to predict the likelihood of lamb survival from birth weight, litter size, lambing ease, udder score and ewe age.

Factor*	Estimate	SE	z value	Pr (> z)
Intercept	-4.825	1.2716	-3.794	<0.001
Birth weight, kg	2.043	0.5054	4.041	<0.001
Birth weight, kg ²	-0.147	0.0527	-2.800	0.005
Litter size: 2	0.029	0.3815	0.075	0.940
Litter size: 3	-0.046	0.4460	-0.104	0.917
Unassisted Lambing ease:	2.378	0.3541	6.717	<0.001
Udder score: 3	-0.647	0.2580	-2.507	0.012
Udder score: 4+	-0.637	0.3760	-1.694	0.090
Ewe Age, years	-0.273	0.1312	-2.082	0.037

* Birth weight, kg² = quadratic effect of this factor; litter size 2 = twins; litter size 3= triplets.

Udder Score 3 is considered suitable for rebreeding next year whereas udder scores of 4 and 5 reflect increasing degrees of udder malformation, with score 4 indicating a misshaped udder from

which lambs can still feed independently and score 5 indicating severe malformation requiring human assistance for the lamb to successfully latch onto the teat.

Plots of the likelihood of survival according to BWT and ewe age for lambs born in assisted (Figure 6.4) and unassisted (Figure 6.5) birthing indicated that ewe age has a larger impact on the survival of lambs of assisted birthing but less so in unassisted birthing. In addition, the optimal BWT was between 6 and 8 kg (Figure 6.5) but their survival is reduced above and drastically below such values. In contrast, increasing ewe age resulted in a linear reduction in survival after considering all other significant factors. In addition, lambs from assisted lambing showed a greater reduction in survival with deviation in BWT and ewe age.

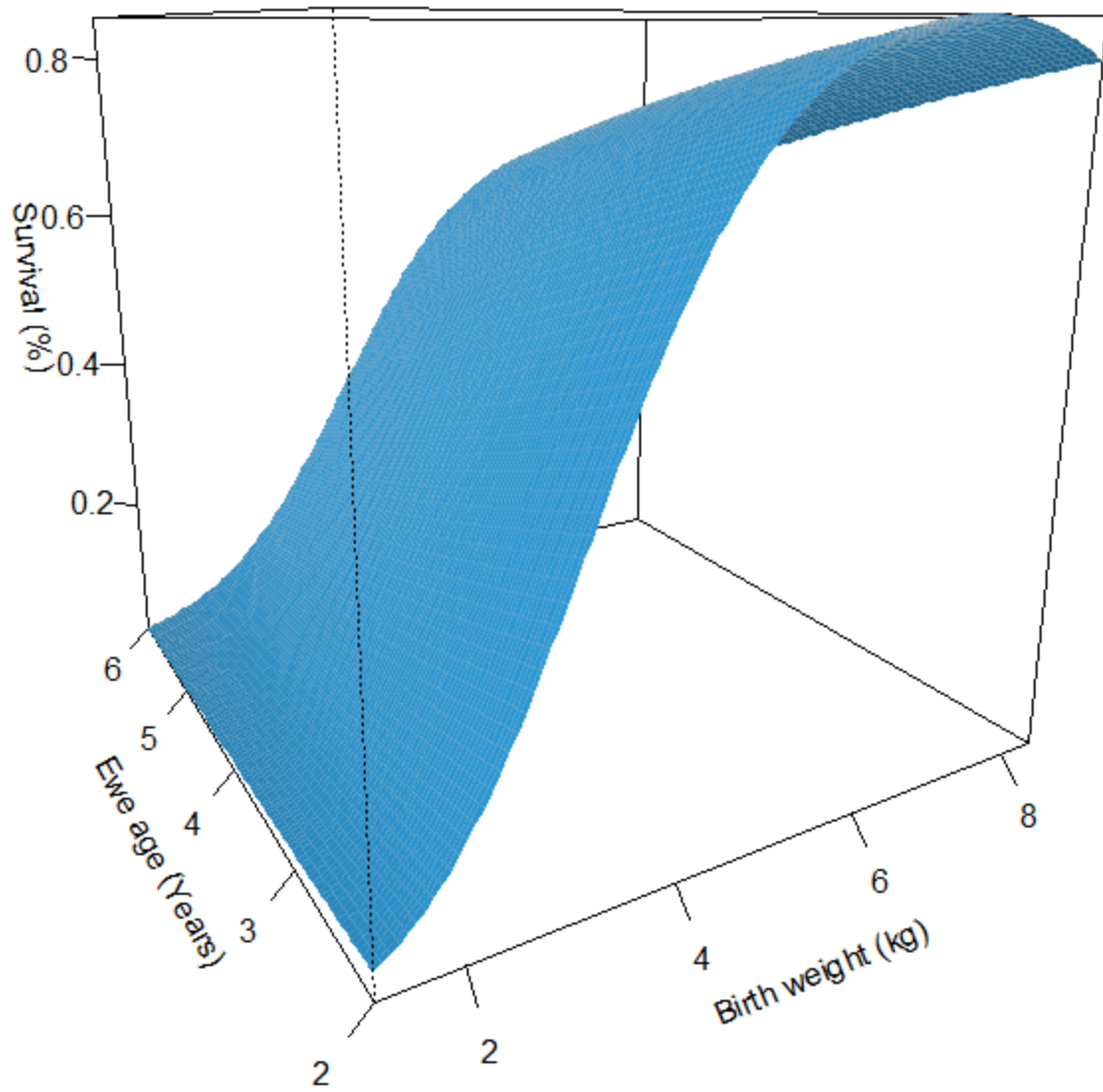


Figure 6. 4. Likelihood of survival of Poll Dorset lambs from assisted lambing according to birth weight and ewe age at lambing.

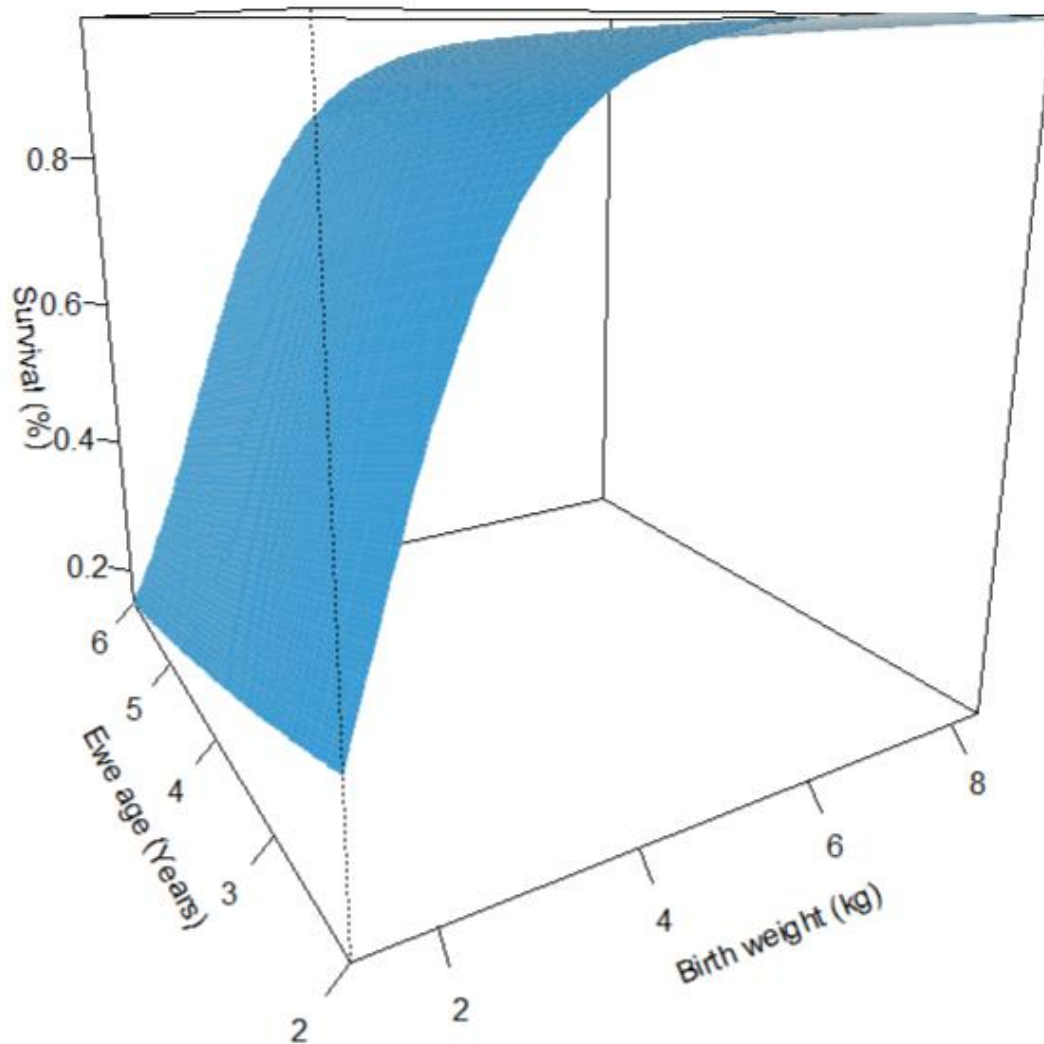


Figure 6.5. Likelihood of survival of Poll Dorset lambs from unassisted lambing according to birth weight and ewe age.

The final models using the remotely collected LW data from the ewes at the time of lambing resulted in a significant pre-lambing LW quadratic term ($P = 0.037$), and litter size ($P < 0.001$; Table 6.5) whereas all other factors including ewe post-lambing LW and ADG were not significant ($P > 0.10$). It is important to highlight that the largest deviance in lamb survival was explained by litter size compared to ewe pre-lambing LW (Table 6.5).

Table 6.5 Effect of ewe liveweight prior to lambing measured remotely using walk-over-weighing technology and litter size on lamb survival.

	Df	Deviance	Residual Df	Residual Deviation	*p < χ^2
Intercept only	-	-	641	463	-
Ewe pre-lambing liveweight, kg	1	2.99	640	460	0.084
Ewe pre-lambing liveweight, kg ²	1	4.36	639	456	0.037
Litter size, No. lambs/ewe	2	44.84	638	411	<0.001

*p < χ^2 = probability >Chi-Square test statistic

The parameters for the prediction equation of lamb survival from ewe pre-lambing LW and LS are shown in Table 6.6 and the plot to visualise the effect is in Figure 6.6 showing the effect of ewe pre-lambing LW on LS is larger for triplet bearing ewes compared to twin and singlet bearing ewes.

Table 6.6 Parameters of a linear regression model to predict the likelihood of lamb survival from birth weight, litter size, lambing ease, udder score and ewe age.

Factor	Estimate	SE	z value	Pr (> z)
Intercept	-11.32	6.057	-1.870	0.061
Ewe pre-lambing liveweight, kg	0.355	0.1280	2.777	0.005
Ewe pre-lambing liveweight, kg ²	-0.0019	0.00066	-2.871	0.004
Litter size, No. lambs/ewe	-1.419	0.226	-6.291	<0.001

SE = standard error

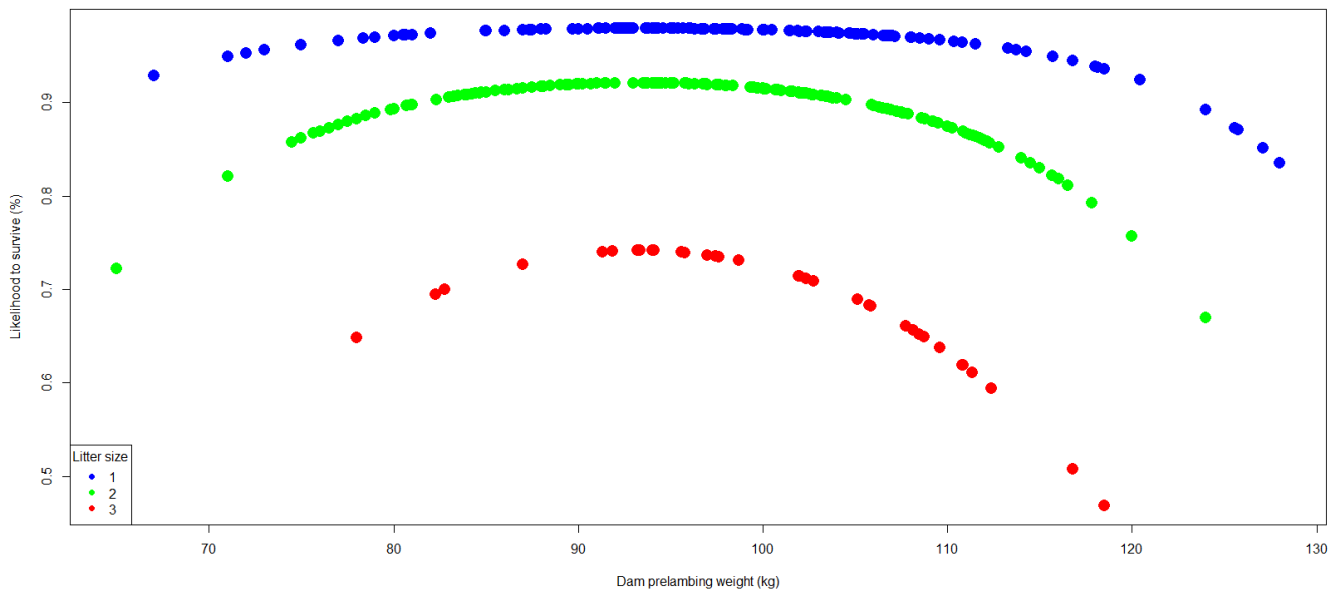


Figure 6.6 Likelihood of survival of Poll Dorset lambs according to the ewe liveweight pre-lambing measured remotely with walk-over-weighing and ewe litter size.

However, it is important to note that LS and lamb BWT are highly correlated and replacing the former by the latter in the model showed that ewe pre-lambing LW only tended to affect lamb survival ($P = 0.058$) and the linear effect of lamb BWT ($P < 0.001$) had the largest impact on lamb survival (Table 6.7).

Table 6.7 Effect of ewe liveweight prior to lambing measured remotely using walk-over-weighing technology and lamb birth weight on lamb survival.

Factor	Df	Deviance	Residual. Df	Residual Deviation	* $p < \chi^2$
Intercept only	-	-	640	459	-
Ewe pre-lambing liveweight, kg	1	3.80	639	455	0.051
Ewe pre-lambing liveweight, kg^2	1	3.60	638	451	0.058
Lamb birth weight, kg	1	50.70	637	400	<0.001
Lamb birth weight, kg^2	1	7.92	636	393	0.005

* $p < \chi^2$ = probability $>$ Chi-Square test statistic

The parameters of the prediction equation of lamb survival according to ewe pre-lambing LW and lamb BWT is shown in Table 6.8 and its visualisation in Figure 6.7 which showed that heavier ewe pre-lambing LW had a larger detrimental effect on the survival of heavier compared to lighter lambs.

Table 6.8 Parameters of a linear regression model to predict the likelihood of lamb survival from birth weight, litter size, lambing ease, udder score and ewe age.

Factor	Estimate	SE	z value	Pr (> z)
Intercept	-15.16	6.548	-2.315	0.021
Ewe pre-lambing liveweight, kg	0.223	0.134	1.659	0.097
Ewe pre-lambing liveweight, kg ²	-0.0013	0.00065	-1.837	0.066
Lamb birth weight, kg	2.59	0.648	3.996	<0.001
Lamb birth weight, kg ²	-0.191	0.0658	-2.913	0.004

SE = standard error

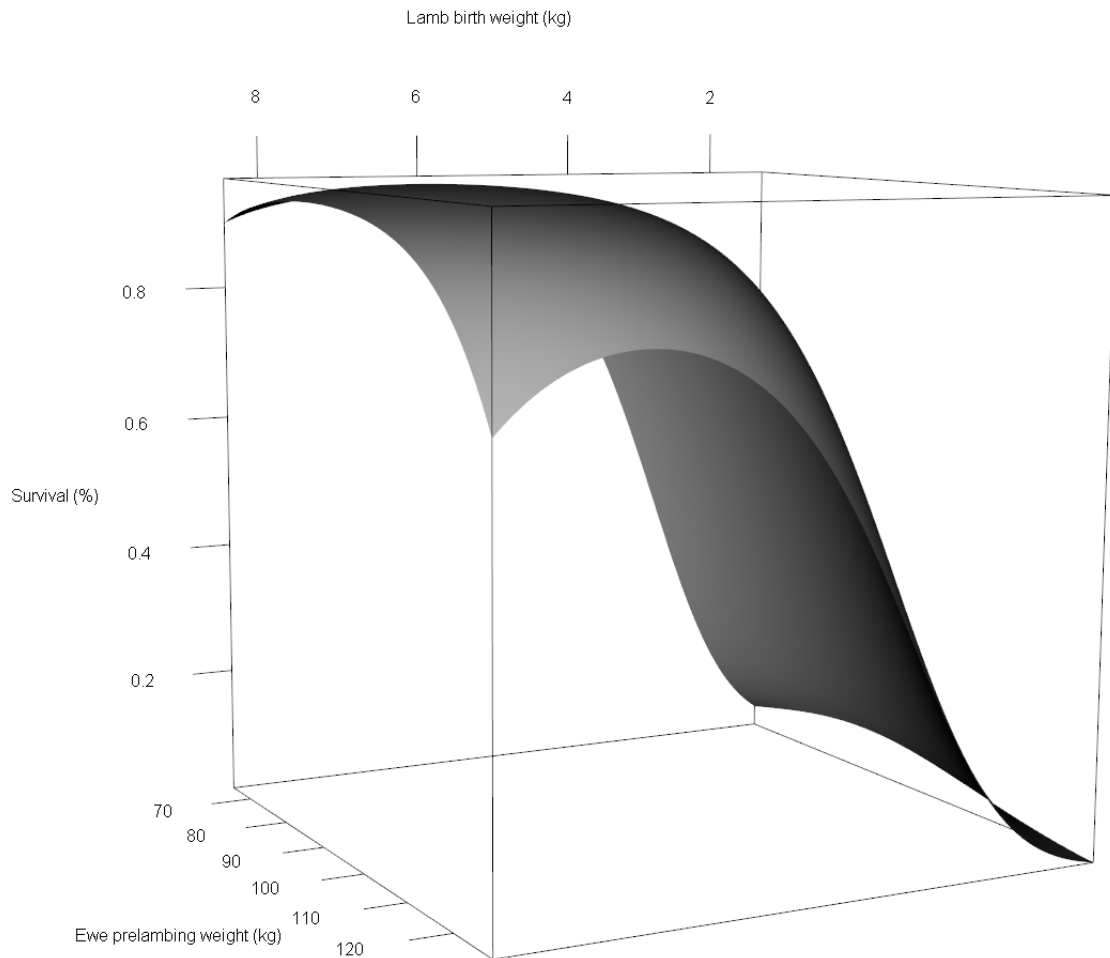


Figure 6.7 Likelihood of survival of Poll Dorset lambs according to the ewe liveweight pre-lambing measured remotely with walk-over-weighing and lamb birth weight.

6.5 Discussion

This study aimed to identify and evaluate the key biological and management factors influencing Poll Dorset lamb survival, with a specific focus on BWT, ewe age, GL, LE, sex, MWL, temperament, udder scores, and LS. In addition, the present study aimed to explore the potential benefit of using WOW technology to manage LS from LW monitoring of ewes before lambing. It was hypothesised that these factors would significantly affect LS both individually when placed in the same model and through their interactions, and that the inclusion of higher-order interactions in the model would improve explanatory power. The results partially supported this hypothesis. In the initial model

including only categorical predictors, LS and LE emerged as significant main effects explaining the largest variation in survival, whereas udder score and MWL had a weak effect, and all other main effects and interactions were not statistically significant and were excluded. In the full model incorporating both categorical variables and covariates, BWT explained the largest variation in lamb survival, but LS became a minor factor affecting survival. These results may be due to BWT 'absorbing' much of the effect that LS had in the categorical model and suggests that the main issue with birth multiples arises from lower BWT. However, the anticipated benefit of incorporating higher-order interactions was not substantiated by the results.

These findings are consistent with the existing literature, which has shown that BWT plays a critical role in lamb survival (Smith, 1977; Oldham et al., 2011; Hinch & Brien., 2013). Studies have suggested that lambs born with lower BWT are at a higher risk of mortality due to underdeveloped physiological systems, i.e. nutritional, reproductive, immunological systems (Simões et al., 2021), and an inability to maintain body temperature due to low body reserves (Hinch & Brien., 2013). Conversely, excessively high BWT can also result in difficult births, leading to an increased risk of injury or asphyxia during delivery, which may impair survival (Hinch and Brien., 2013). Earlier research by Dwyer & Bünger (2012) in Suffolks and Texels, found that heavy-weighted singleton lambs required greater veterinary assistance at delivery than other LS. The quadratic relationship observed in the present study indicated an ideal BWT range to maximise survival of Poll Dorset lambs between 6 and 8 kg.

Moderate increases in BWT are associated with improved survival, but excessively high BWT elevates the risk of dystocia, particularly among single-born lambs (Bruce et al., 2021). This creates a negative relationship between BWT and LE, where heavier lambs, despite their advantages in early survival, face an increased likelihood of birthing complications that can negatively impact survival. Thus, genetic selection for increased BWT may enhance lamb survival rate, but careful management of BWT remains critical to optimizing both LE and survival (Hatcher et al., 2009). Importantly, the

present study placed all these potential factors into the same statistical model (LS, LE, and BWT) so the source of variation in observed lamb survival could be assigned to the correct factor.

Interestingly, LE was the second most influential factor in both the categorical and covariate models, which suggests that the effect of LE may influence survival beyond BWT and LS through other mechanisms not measured in the present study such as shoulder width and head diameter of the lamb, and pelvic area and metabolic status of the ewe. In earlier research into Suffolk and Texel breeds, 28% and 34% of lambs requiring major assistance were correctly presented, suggesting that factors such as lamb size or shape may contribute more significantly to birth difficulty in these genotypes (Dwyer & Bünger, 2012). It is further proposed that such difficulties may also be linked to maternal characteristics, including reduced pelvic dimensions, which can result in fetopelvic disproportion and obstruct normal delivery (Fogarty and Thompson, 1974; (Dwyer & Bünger, 2012). Therefore, further research to understand the factor's affecting LE is recommended.

Results of the present study indicated that gestation length was not associated with survival rate in a model where BWT and LE had the largest influence on lamb survival. One potential explanation for this counterintuitive result is that the occurrence of dystocia in longer gestations associated with oversized lambs (Refshauge et al., 2015) could mainly be due to BWT and thus GL is not significant in a model that contains BWT. In addition, obstructive interference during birth, ewe exhaustion, or ill-health (Refshauge et al., 2015) may have been represented through LE recording in the present study. Additionally, studies have shown that lambs born prematurely or with shorter gestations face increased risks of hypothermia, poor immune function, and an inability to nurse effectively, all of which contribute to high mortality rates (Refshauge et al., 2015).

LE is a well-documented factor reducing lamb survival (Dwyer, 2008). Lambs born through difficult deliveries, which may be characterized by factors such as dystocia, low vigour, or prolonged labour, are more likely to experience complications, including injury, oxygen deprivation, or failure to thrive

post-birth. These findings underscore the importance of managing birth ease to improve lamb survival, particularly in high-risk pregnancies.

MWL emerged as a weak predictor of lamb survival with lambs born to ewes with shorter wool having 7% higher survival rate. This agrees with earlier findings by De Barbieri et al. (2018) in Corriedale sheep, who demonstrated that the time of shearing ewes could significantly influence lamb survival and birth weight, with mid-pregnancy shearing associated with heavier lambs and improved survival rates compared to lambs born to unshorn ewes. However, management practices, including provision of shelter, good nutrition, and lambing supervision, may have further minimized the impact of maternal fleece characteristics in the present study. Additionally, stronger predictors such as birth weight and birth ease showed significant associations with lamb survival in both models, potentially masking any smaller effects of MWL.

Results of the present analysis demonstrated that the inclusion of interactions between factors did not contribute substantially to the explanation of variation in lamb survival. These findings are critical in guiding both interpretation and application and may suggest that the influence of these variables on survival is primarily additive and independent, rather than antagonistic, multiplicative or synergistic. Although it is theoretically plausible that combinations of maternal and offspring characteristics could interact to affect neonatal survival, such patterns were not supported by results of the present study.

The implications of these findings are both practical and theoretical. From a management perspective, they suggest that targeted interventions should prioritise factors with demonstrated impact—namely, ensuring optimal birth weight through appropriate nutrition and monitoring, minimising the incidence of difficult lambing through selective breeding or timely lambing assistance, and culling older ewes where possible.

Both models reinforce the central importance of key biological predictors such as BWT, LE, and udder score in determining lamb survival, pointing where interventions should focus rather than

relying on indirect or complex combinations of less impactful variables. This approach supports more efficient allocation of resources in flock management and aligns with evidence-based strategies to improve lamb viability and overall productivity.

Previous research by Scales et al. (1986) showed that, in New Zealand Romney × Suffolk ewes, lamb mortality was relatively unaffected by ewe pre-lambing LW across the range of 40–80 kg. However, ewe LW below 40 kg, mortality rates increased sharply in both single and multiple births. An important finding from the present study was that remotely collected LW of ewes pre-lambing can influence lamb survival. The effect of pre-lambing ewe LW on lamb survival reduced lamb survival to a larger extent in triplet-bearing ewes compared to twin and singlet bearing ewes, with lamb survival declining at ewe pre-lambing LW below 85 kg and above 100 kg. In contrast, the decline in lamb survival dropped when the ewes had below 75 kg and above 110 kg pre-lambing in twin-bearing ewes and only above 120 kg of single-bearing ewes. Therefore, these results suggest that managing pre-lambing LW of ewes is more important and it should be done within a narrower pre-lambing LW in triplet compared to twin bearing ewes, whereas singlet bearing ewes are less affected. Up to the authors best knowledge, this is the first time such results are reported in the scientific literature and demonstrate the potential applications of real-time LW monitoring of ewes during gestation to help managing ewes to reduce Poll Dorset lamb mortality. Furthermore, the model containing both ewe pre-lambing LW and lamb BWT demonstrated that survival is particularly reduced in heavier lambs born from heavier ewes (over 110 kg). This information is important for managing survival of lambs, but it has the limitation that BWT is unknown unless lambing rounds to weigh lambs at birth is recorded.

The implications for breeding and management of these results are significant. In terminal sire breeds such as the Poll Dorset, where selection pressure is often placed on growth traits, the balance between lamb viability and birthweight becomes a crucial concern. Hall et al. (1994) demonstrated that net reproductive rate is a key driver of genetic progress, flock profitability, and the flow of improved genetics into the lamb industry. However, high reproductive rates alone are

insufficient if dystocia and SME compromise survival outcomes. Scales et al. (1986) showed that nutritional management can mitigate some of these risks, particularly for multiple-bearing ewes, while Jacobson et al. (2020) identified ewe fitness to lamb as a critical area for future research. Together, these studies point toward a model of integrated flock management where genetic selection, targeted nutrition, and close attention to ewe condition work synergistically to optimise survival. Future research should explore the effect of environmental conditions and their interaction with maternal wool length on lamb survival outcomes with longitudinal studies tracking lamb survival across different seasons or climates.

6.6 Conclusion

The present study contributed to a more refined understanding of lamb survival capturing the complexity and nuance of a complex biological system. Results support that lamb survival is largely shaped by direct, biologically grounded effects such as lamb birth weight which is linked to litter size, and ewe-lambing LW as measured remotely using WOW technology. Results suggest that WOW technology could be used to improve the management of both ewe LW and lamb BWT, which could help reduce lamb mortality. However, this hypothesis should be evaluated further with field research and nutritional intervention on the ewes during late gestation to be confirmed. Results of the present study do not rule out the possibility of interactions in other populations or under different environmental, managerial, or genetic conditions. However, results also highlight the importance of empirical testing before assuming the presence of complex interdependencies.

BWT, litter size, LE, udder score, and ewe pre-lambing LW were the primary determinants of lamb survival. These findings underscore the importance of achieving optimal birth weights to improve lamb survival and overall flock productivity. Future research should continue to explore the biological mechanisms underlying these associations with lamb survival and investigate factors across different breeds, environments, and management systems to ensure the broader applicability of these insights.

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6.8 Data Availability Statement

Data available on request from L.A.G. due to restrictions.

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6.10 Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study or in the collection, analyses, or interpretation of data or in the writing of the manuscript.

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Chapter 7

General Discussion and Conclusions

This chapter consolidates the principal findings from the preceding chapters and integrates them to provide an overarching general discussion and conclusions for the thesis. It considers the practical implications of the research, highlights its limitations, and identifies areas where further investigation would be valuable for the Australian sheep industry. The central theme of this thesis has been the evaluation and application of in-paddock monitoring technologies for grazing Poll Dorset sheep, with a particular emphasis on liveweight (LW) and growth trajectories whilst also providing new knowledge on factors contributing to lamb mortality.

At the outset of this research, two guiding conditions were established to frame the scope and ensure the applied relevance of the work. Firstly, all investigations were to be conducted on commercial sheep enterprises, thereby situating the study within authentic production environments and enhancing the practical application of the findings. Secondly, this thesis investigated the application of walk-over-weighing (WOW) technology as a precision livestock farming (PLF) tool for monitoring LW dynamics in grazing Australian sheep production systems. The research integrated technological evaluation with biological modelling to examine associations between LW trajectories, reproductive performance, early-life growth, and lamb survival under commercial grazing conditions. As the study was observational in design, the findings describe predictive and associative relationships rather than direct causal effects of WOW-informed management on production outcomes. The first objective was achieved with 9 individual commercial sheep businesses being used to either test, develop or apply the developed WOW technologies within the grasslands or rangelands of New South Wales, Australia from 2019 to 2023 (see Appendix A for photos for the 2 designs WOW systems used). The results for each of these farms was only

used in chapter 3 to evaluate the precision and accuracy of WOW technology. The second objective was achieved and underpinned the results of chapters 4 to 6 within this thesis which focussed solely on Poll Dorset ewes and lambs where the best quality data was available including pregnancy scanning, lambing, and weaning linked to each individual animal. All other farms except one with Border Leicester had Merino, where lambing data is not collected due to the potential detrimental effects on mismothering. Therefore, these farms were not as suitable for developing algorithms and understanding the potential of WOW technology in sheep enterprises.

To the author's best knowledge, no previous research has undertaken such a detailed longitudinal analysis of mortality, LW, and ADG in purebred Australian Poll Dorset ewes and lambs, nor examined how the integration of biological and management practices shapes lamb survival across consecutive years. This new research provides producers latest information that is important for improving survival outcomes and optimising flock productivity. Central to this investigation was the hypothesis that WOW systems may capture high frequency LW data with sufficient accuracy to detect and predict factors linked to key productivity and welfare outcomes in sheep, including lamb survival, reproductive efficiency, and growth trajectories in pregnant and lactating ewes and their offspring.

Chapter 3 evaluated the accuracy and precision of WOW systems against traditional YW, demonstrating a strong linear association ($r^2 = 0.89$) across 5,786 paired observations. These findings confirm WOW as a reliable tool for large-scale sheep production and encourages future research in predictive modelling, genetic evaluation, and welfare. All chapters of the present thesis collectively demonstrate that WOW technologies have the capacity to progress beyond experimental validation and into widespread commercial adoption. The findings highlight the scalability of WOW from controlled trials to real-world production environments, confirming the robustness of these tools under extensive grazing conditions. In doing so, Chapters 4 and 5 underscore the central role of PLF systems in enabling informed, data-driven decision-making for livestock enterprises. Chapter 6 investigated the biological and managerial determinants of lamb survival, demonstrating that lamb

birth weight, ewe pre-lambing LW and lambing ease were the most significant predictors, with both traits exerting strong and consistent effects on neonatal survival. The incorporation of both categorical and continuous variables advanced predictive modelling of survival in Poll Dorset lambs and underscored the importance of managing key risk factors such as dystocia and suboptimal pre-lambing LW in commercial sheep systems.

7.1. Main Findings

The main findings of this thesis included the evaluation and application of in-paddock monitoring technologies of LW within extensive sheep production system, the causes of mortality in Poll Dorset lambs in early life, the relationship between ewe and lamb LW and average daily gain (ADG) derived from remotely collected data. Collectively, these findings provide valuable insights into the biological factors that shape reproductive outcomes and lamb survival in extensive grazing systems. This research established a strong foundation for further investigation and research into the specific drivers underlying lamb mortality and lamb growth.

The findings presented in Chapter 3 confirmed that WOW systems generate accurate and consistent LW measurements when benchmarked against traditional YW. This validation provides producers with confidence in the adoption of WOW technologies as a reliable tool for monitoring sheep performance under large-scale, commercial grazing conditions. This study built upon the foundational contributions of González et al. (2014) in cattle and Brown et al. (2013, 2014) in sheep. However, the work of Brown et al. (2013, 2014) centred predominantly on descriptive analyses and statistical comparison between WOW and traditional YW measurements, whereas the present research advanced these approaches by adopting and extending the more sophisticated analytical framework introduced by González et al. (2014) in beef cattle studies.

Specifically, this framework incorporates penalised B-spline smoothing to model LW trajectories, in conjunction with rigorous outlier detection and data-cleaning procedures, thereby enabling a more

robust and meaningful interpretation of longitudinal LW patterns in Poll Dorset sheep. Through this approach, the present thesis delivered a methodological innovation to the field of sheep production science, bridging the gap between earlier descriptive validation studies to more advanced predictive modelling frameworks. In doing so, it provides new opportunities to enhance on-farm management practices while also generating insights that can be leveraged in future genetic evaluations and welfare-focused investigations. The data sets used in Chapter 3 comprised of 5,786 paired observations. Analysis revealed a strong linear association between WOW and YW measurements, with a high coefficient of determination ($r^2 = 0.89$), indicating that a substantial proportion of the variance in one measure was accounted for by the other. Although the analysis revealed significant mean and systematic biases, the low contribution of these biases to total error, high precision, and major differences between WOW and YW (e.g. time off feed and water for YW) suggest that WOW is a suitable and accurate tool to monitor sheep LW under grazing conditions. This analysis further provided an accurate quantification of bias, for predictive modeling and industry applications for decision-making. In addition, the findings from chapters 3 to 6 further demonstrated that WOW technology is able to detect both ewe and lamb LW differences associated with expected biological factors such as litter size and lamb survival.

This offered deeper insight into the operational strengths and limitations of the WOW technology. By integrating high resolution longitudinal data with advanced statistical modelling, the present thesis moved beyond simple correlation testing. Such an approach is critical for future PLF research, where data collection is translated to management decisions affecting nutrition, health, welfare, and enterprise profitability. Moreover, precision in livestock measurements is of critical importance because it can affect the accuracy of management decisions. For instance, the fact that WOW data detected differences between ewes and lambs LW according to litter size suggests that the technology could effectively be used for nutritional management to achieve target LW throughout critical production phases such as gestation and lactation. However, future research should include

the development and validation of alternative and advanced measurement technologies and analytical approaches to minimise bias, enhance accuracy, and evaluate their long-term implications for animal health, productivity, and sustainable flock management. Amongst these, LW measurements using machine vision (image analysis) could offer an alternative to sheep weighing using load bars, and evaluation of the accuracy of WOW technology against YW under more controlled conditions where the time between last WOW and YW is minimised could result in higher accuracy. This may reduce changes in LW due to defecation and urination between the paddock and yards, which was not possible to control under the commercial conditions of the present thesis.

Chapters 4 validated work presented in Chapter 3, demonstrating that WOW systems can provide relevant data under extensive grazing conditions. By applying statistical approaches, previously validated in intensive small-scale trials (González et al., 2014), these chapters confirmed the scalability and robustness of WOW systems and associated algorithms in commercial sheep enterprises. Collectively, these findings highlight the transition of PLF tools from experimental validation to practical applications, reinforcing their capacity to support data driven decision making. The use of this new knowledge may contribute to the broader digital transformation of livestock systems, where performance and behavioural data can increasingly be captured remotely (Banhazi et al., 2011). In particular, the integration of EID with WOW systems enables real time monitoring of sheep performance across multiple production phases, including pre-weaning, post-weaning, joining, lambing, lactation, and beyond.

Chapter 4 focused on evaluating LW and ADG changes in individual ewes as they progressed from late pregnancy into lactation. The results showed that the interaction between SLS and date significantly influenced LW in both years and affected ADG in 2021 but not in 2022, where only date had a significant effect. These findings demonstrate that longitudinal monitoring of LW trajectories through pregnancy and lactation can be achieved under commercial conditions using WOW systems. Importantly, mixed effects models effectively detected within- and between-animal variation due to

animal physiological state, management and environmental factors. Therefore, WOW data and subsequent analyses can shift the focus from sporadic LW snapshots obtained through YW to more frequent growth curves, offering a deeper understanding of ewes and lambs performance over time.

Chapter 5 extended this analysis to Poll Dorset lambs, demonstrating the potential of frequent LW monitoring to inform data driven management strategies aimed at maximising genetic potential through managing growth trajectories. The study examined the effect of weaning litter size (WLS; single, twin, triplet) on LW and ADG across three years using in-paddock WOW. A total of 1,213 artificially conceived, mixed-sex lambs were initially included, with rigorous data cleaning yielding a final cohort of 830 animals with consistent and longitudinal data. This analysis allowed the estimation of both baseline differences in LW due to litter size and temporal divergence during growth. Significant interactions between WLS and date were observed for LW and ADG in 2020 and 2022, indicating that litter size affected not only average growth outcomes but also the trajectory of LW and ADG. In 2020, triplet lambs remained consistently lighter than singles and twins, whereas in 2022, single lambs were heavier than both twins and triplets. By contrast, no significant interaction was observed in 2021, suggesting that environmental or management factors may have moderated the influence of litter size in that year. The ADG patterns closely reflected LW in years with significant interactions, reinforcing the conclusion that litter size influences both attained body mass and the dynamics of growth over time.

Chapters 4 and 5 showed that remotely acquired LW and ADG using WOW systems provide valid alternatives to YW with high frequency from individual ewes and lambs and detected differences attributable to litter size in commercial grazing systems. Although this study established a practical and minimally invasive proxy for comparison with conventional YW assessments, further research is warranted to explore the broader potential of WOW systems. Such WOW systems could operate as early warning tools for health and welfare challenges, including reproductive losses, parasitic burden, nutritional inadequacies, and threats to the survival of lambs and their dams.

Chapter 6 concentrated on identifying and analysing the key biological and managerial factors influencing lamb survival, highlighting the complex interplay between ewe physiology, environmental conditions, and flock management. Generalised linear modelling across two lambing seasons revealed that variation in lamb survival was primarily explained by a small set of high-impact predictors. Birth weight emerged as the most significant factor, displaying a pronounced quadratic relationship ($P < 0.001$), where lamb survival was reduced at both low and high BWT. Lambing ease (LE) was also highly influential ($P < 0.001$), with unassisted births conferring substantially higher lamb survival compared to assisted lambing, underscoring the risk of dystocia as a major contributor to perinatal loss. Litter size strongly affected survival, with singles and twins showing higher survival than triplets ($P < 0.05$), whereas udder conformation and maternal wool length exhibited only weak tendencies ($P < 0.10$). Secondary traits such as ewe age and udder structure showed variable effects, reflecting their more indirect contribution to neonatal viability. Importantly, the combined use of categorical and continuous covariates within a multivariate logistic regression framework captured both non-linear and interaction effects, thereby improving predictive precision.

Remotely collected ewe pre-lambing LW, measured via WOW, also influenced lamb survival in a quadratic manner. Survival declined at both low and high ewe pre-lambing LW thresholds, with the greatest sensitivity observed in triplet-bearing ewes (reduced lamb survival below 85 kg and above 100 kg), followed by twins (below 75 kg and above 110 kg), and singles only affected at extreme ewe pre-lambing LW (>120 kg). Statistical models confirmed a significant quadratic effect of ewe pre-lambing LW ($P = 0.037$) and a strong effect of litter size ($P < 0.001$), while post-lambing LW and ADG were not significant predictors ($P > 0.10$). When lamb birth weight was substituted for litter size, birth weight emerged as the dominant determinant (linear: $P < 0.001$; quadratic: $P = 0.005$), whereas ewe pre-lambing LW was only marginally significant ($P = 0.058$). Importantly, heavier ewes carrying heavier lambs exhibited reduced survival, suggesting that excessive maternal condition increases the risk of dystocia and perinatal complications with triplet lambs being more affected. This information

highlights the importance of ultrasound scanning and nutritional management to control gestational LW of triplet bearing ewes, which require a narrower LW range to maximise survival.

Collectively, the findings support a conceptual framework in which lamb survival is jointly influenced by pre-lambing ewe LW, lamb birth weight, and post-lambing ewe LW dynamics, with litter size acting as a critical modifier of these relationships. Walk-over-weighing provides the measurement resolution required to quantify these interactions by generating continuous maternal LW trajectories that capture non-linear responses and biologically meaningful thresholds. In contrast to sporadic yard-based measurements, WOW enables the identification of risk profiles that develop over time and may precede adverse outcomes. The longitudinal LW data generated through WOW provide a continuous representation of maternal physiological state, enabling the identification of predictive associations between ewe LW profiles, lamb birth weight, growth trajectories, and survival outcomes. These predictive associations are statistically robust relationships that allow the identification of risk profiles and biologically relevant thresholds, particularly where non-linear responses and litter size-specific sensitivities were observed.

These relationships can be integrated into a framework linking WOW data to biological outcomes. In this framework, ewe LW trajectories derived from WOW during late gestation can influence lamb birth weight and lambing ease, which together determine neonatal survival probability. Post-lambing ewe LW trajectories provide additional context regarding maternal capacity during early lactation. Management interventions, including litter size-specific nutritional strategies and targeted monitoring of ewes outside optimal LW ranges, can be positioned within this framework to illustrate how remotely collected data could inform practical decision-making.

The present thesis advanced both methodological development and evaluation of technology and biological understanding of lamb survival in extensive sheep systems through the integration of technology, data processing and accuracy evaluation (Chapter 3), longitudinal ewe LW dynamics

(Chapter 4), lamb growth trajectories (Chapter 5), and multivariate survival modelling (Chapter 6). Model structures throughout the studies were selected based on the biological hierarchy of the data and the need to account for repeated measurements within animals. Random effects were included to account for within animal correlation and unknown individual variability. Penalised B-splines were used to model LW trajectories due to their flexibility in capturing non-linear patterns. Outliers were identified using statistical and biological criteria and removed where consistent with measurement error. Model assumptions were evaluated through residual diagnostics, and sensitivity analyses confirming that conclusions were robust to alternative model specifications. The results demonstrate that precision livestock technologies such as *WOW* can be embedded within biologically informed analytical frameworks to support data-driven management aimed at improving productivity, animal welfare, and reproductive efficiency of sheep under commercial grazing conditions.

7.2 Limitations of the Study and Future Research Opportunities

The present thesis has advanced knowledge in sheep production by demonstrating that high frequency, automated LW data from *WOW* technology provides a non-invasive and efficient means of monitoring growth and performance in extensive grazing systems. This thesis also acknowledges several limitations and boundary conditions that should be considered when interpreting the findings. Firstly, coverage bias is inherent in opportunistic data collection systems, as animals that traverse the *WOW* infrequently such as low-ranking ewes in large paddocks or during wet conditions may be under-represented in the dataset. Second, hardware-related issues, including load cell drift, electronic tag misreads, and the influence of station placement relative to water and mineral sources, could affect both data yield and quality, highlighting the importance of ongoing calibration and system redundancy. Third, the generalisability of results requires caution, while the Poll Dorset populations and environments examined are broadly representative of southern Australian systems, variation in breed, pasture type, and climatic conditions are likely to influence both animal

behaviour at EID readers and growth potential. Finally, although the models presented here demonstrate strong surveillance capacity, causal attribution remains limited. Disentangling the relative contributions of environmental conditions, nutrition, subclinical disease, and other factors will require future work that integrates WOW with complementary sensor technologies, such as accelerometry, GNSS, rumination monitoring, and thermal imaging, which are becoming increasingly commercially available within precision livestock management.

The findings align with previous research indicating that walk-over-weighting (WOW) can move beyond basic monitoring towards predictive management by supporting earlier inference of changes in individual animal and flock performance. Despite these advances, the present thesis was limited to growth and reproduction traits and did not directly address specific health and welfare outcomes, such as internal parasitism. Investigation of these factors was beyond the scope of the thesis but represents an important direction for future research, particularly through trials incorporating environmental stressors and behavioural data to assess how health and welfare challenges influence LW dynamics across production stages in rams, ewes, and lambs. Further advances in web-based data platforms and automated data transfer are also expected to improve the efficiency, scalability, and integration of WOW technologies, thereby supporting broader adoption of precision livestock management tools in commercial sheep enterprises. An additional limitation concerned the potential impact of sire and dam genetics on mortality, LW and ADG, which was not within the scope of the present research. Therefore, future research may pair genetic information with WOW LW monitoring of pre-weaned Poll Dorset lambs to quantify its effects on early growth and partition genetic versus environmental variance. Discussions between researchers and producers involved in the trials revealed strong interest in developing improved methodologies to quantify sire effects on LW and growth trajectories under commercial conditions. Future research could focus on evaluating how Australian Sheep Breeding Values (ASBVs) translate into LW and ADG patterns across different environmental conditions. Such studies would help determine the effect of genotype × environment

interactions on such patterns and eventually discover new phenotypes from longitudinal LW and ADG data collected using WOW stations. For example, the LW patterns throughout seasons could help identifying those animals that are better able to cope with changes in environmental and management conditions, or better able to cope with tough seasons.

Importantly, these associations reflect underlying biological mechanisms that are consistent with established physiological principles. Maternal LW during late gestation reflects energy balance, foetal development, and maternal tissue mobilisation, all of which influence lamb birth weight and lambing ease. In turn, lamb birth weight represents a critical biological intermediary, influencing thermoregulation, vigour, and susceptibility to dystocia, thereby directly affecting survival probability. Similarly, longitudinal lamb LW and growth trajectories reflect the combined effects of maternal capacity, milk production, and sibling competition, particularly in multiple births, amongst other factors such as grazing ability and genetic potential. The ability of WOW systems to detect differences in LW trajectories demonstrate that remotely collected LW data can capture meaningful biological variation relevant to animal performance and welfare.

To date, few published studies have offered extended, longitudinal LW data from commercial flocks in near real time. This makes the current investigation a valuable contribution to PLF literature and practice. It builds upon previous efforts (Brown et al., 2012; González et al., 2014; Gonzalez-Garcia et al., 2018; Bates et al., 2023; Leroux et al., 2023) by demonstrating novel WOW setups, enhanced algorithms for data processing, and integration with producer-accessible web platforms. This improves scalability and accessibility, vital for expanding PLF adoption beyond intensive operations or research settings. Collectively, the overall findings underscore the potential for digital phenotyping tools to inform more precise, welfare-oriented, and performance driven management strategies in extensive sheep production systems. The present thesis evaluated longitudinal LW trajectories and growth performance across late pregnancy and lactation of ewes and lambs until weaning, with temporal changes due to physiological, environmental, management, and genetics

effects although the relative contribution of each was not within the scope of the present thesis.

This highlights a key gap in knowledge which could be filled using WOW platforms with integration of other data streams, offering considerable promise for future research into the health and welfare of ewes and lambs, as well as opportunities for the commercialisation of WOW procedures and analytical algorithms. Although the study acknowledged certain limitations specific to the Poll Dorset investigation, it generated new insights into the biological and environmental factors shaping lamb survival and overall flock performance.

However, it is essential to distinguish predictive association from causal inference. Although the statistical models presented in this thesis demonstrate strong associations between ewe LW, lamb birth weight, litter size, and survival, these findings do not establish direct causality, as they are derived from observational data under commercial conditions. Ewe LW, for example, may act both as a direct biological driver and as an integrated indicator of nutrition, genetics, and environmental influences. Thus, although predictive models provide reliable tools for identifying animals at elevated risk of adverse outcomes, causal inference would require controlled experimental manipulation of nutritional or management variables.

Finally, the practical implementation of WOW data in real-world lies in its ability to operationalise these predictive relationships into actionable management decisions, which still require further research and evaluation. Continuous monitoring enables early identification of ewes outside optimal LW ranges, facilitating targeted nutritional interventions, improved reproductive management, and enhanced survival outcomes. However, WOW systems provide a practical and scalable framework for improving productivity, animal welfare, and management precision in extensive sheep production systems.

7.3 Conclusions

The present thesis tested the hypothesis that in paddock WOW systems can generate high frequency LW data with sufficient accuracy to monitor and predict key productivity and welfare outcomes in sheep. The findings demonstrated that WOW technology is capable of reliably capturing longitudinal LW trajectories under commercial grazing conditions. Furthermore, such data provided valuable insights into lamb survival, reproductive efficiency, and growth dynamics in pregnant and lactating ewes and their offspring. Collectively, this research establishes WOW as a practical and scalable PLF tool, supporting the shift toward data-driven decision-making in extensive sheep production systems.

Across multi-season commercial cohorts, WOW data were evaluated against yard data, filtered for data quality, and ADG estimated. Linear mixed-effects and generalized models showed that WOW-derived LW and ADG captured biologically meaningful variation among individual animals that were linked to grouping factors such as litter size. Departures from optimal pre-lambing ewe LW signalled elevated risk of dystocia, suboptimal birthweight, and early life loss. Importantly, the approach reduces handling stress and labour while improving the timeliness of decision making which was important to the producers involved in the research. Limitations include opportunistic sampling, and context-specific generalisability. Nevertheless, the evidence demonstrates operational utility of WOW technology. Future research should link WOW to actions that improve economic endpoints, incorporate complementary sensors, and quantify sire and dam genetic effects on longitudinal LW and ADG trends. Overall, WOW provided a scalable foundation for proactive, welfare positive management in Australian sheep systems.

The application of PLF tools such as WOW requires continual refinement as technologies evolve. This research demonstrated that WOW platforms developed from commercially available hardware and software can meet the rigorous demands of commercial sheep production under extensive grazing conditions. Comparative evaluation against conventional yard-based weighing confirmed that in-

paddock WOW delivers high frequency data critical for future health and welfare monitoring in sheep. A persistent challenge, however, is the limited availability of data processing and visualisation techniques, with many producers still lacking access to real-time analytical tools capable of translating raw LW into meaningful operational and financial insights. Addressing this limitation will be central to maximising the adoption and impact of PLF technologies in commercial enterprises. The findings of the present thesis further demonstrate that the value of PLF lies not only in automated data capture but also in the development of integrated pipelines for data quality control, model-based interpretation, and actionable thresholds that enable timely management interventions. By aligning monitoring technologies with user friendly interfaces and predictive models, producers could be empowered to make evidence-based decisions that respond to both individual animal performance and environmental variability. The WOW systems provide frequent monitoring of sheep, are capable of detecting changes in physiological status (e.g. lambing and lactation) and performance and could thereby facilitate proactive flock management. This thesis also highlighted the potential for WOW to track LW dynamics during lactation, which could guide management strategies such as adjustments of stocking rate, pasture allocation, or targeted supplementation without reliance on invasive practices. The successful deployment of WOW under commercial conditions confirmed its utility in generating datasets that support the visualisation of lambing progress, LW recovery during lactation, identification of animals requiring closer attention, lamb growth, and reproductive efficiency.

Demonstrating the capacity of remote monitoring technologies to capture robust and relevant data represents a critical step toward ensuring their value and scalability within the sheep industry. The utility of these systems lies in their ability to generate high frequency, decision ready information that can improve productivity and profitability at both the flock and enterprise level. Although the cost benefit of adoption may change depending on property goals, applications, and labour availability, the ease of integration of WOW into extensive grazing systems highlights their potential

for broad uptake. These technologies provide the foundation for understanding key drivers of mortality, LW dynamics, and growth, thereby supporting a transition from reactive to predictive management.

Within this broader technological framework, this thesis also addressed a significant gap in knowledge by investigating the biological factors associated with lamb mortality of Poll Dorset sheep, a terminal sire breed of major importance to prime lamb production in Australia. Despite their widespread use in crossbreeding systems, no previous research has systematically examined how biological and managerial factors interact to affect lamb survival in this breed, even though survival directly influences profitability, genetic progress, and supply chain efficiency. This thesis quantified several factors affecting lamb survival under real-world production conditions analysing commercial flock records across multiple seasons. These findings provide new scientific insights into breed-specific drivers of neonatal survival and practical applications to improve flock management, reduce lamb losses, and enhance welfare outcomes.

Collectively, the outcomes of this thesis demonstrate that the true value of remote monitoring technologies emerges when they are integrated with other datasets such as pregnancy scanning, biological processes and management practices. Together, these approaches offer a pathway toward more sustainable, efficient, and welfare-focused sheep production systems, positioning precision livestock management as a cornerstone of future industry advancement.

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Appendix A



Figure A.1. walk-over-weighing platform that can be towed from paddock to paddock and set up as a complete unit.



Figure A.2. Birds eye view of the transportable walk-over-weighing platform with merino rams traversing.



Figure A.3. walk-over-weighing platform that requires lifting on to a trailer and dismantling before moving to another paddock.



Figure A.4. Poll Dorset lamb traversing a walk-over-weighing platform in early stages of life at (<4 weeks old).

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