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**The Value of Information**

*Redefining Key Performance Indicators to Support Improvements in Sheep Farming Efficiency*

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# THE VALUE OF INFORMATION:

# REDEFINING KEY PERFORMANCE INDICATORS TO SUPPORT IMPROVEMENTS IN SHEEP FARMING EFFICIENCY


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A dissertation submitted to the University of Bristol in accordance with the requirements for award of the degree of Doctor of Philosophy in the Faculty of Health Sciences

[22,340 words]

# Abstract

Sheep farming has long been associated with low profitability and low operational efficiency compared to other livestock sectors. Evidence to date suggests that this tendency is at least partially attributable to the sector's low level of performance monitoring, an essential source of information to support accurate and timely management decisions, and that farmers' reluctance to monitor, in turn, likely stems from the lack of conviction regarding its tangible benefit. To evaluate the economic value of performance monitoring and thereby facilitate its optimal uptake across sheep farms, this thesis investigated three factors that must be considered to make measured information worthwhile in the commercial context: *accuracy*, *impact*, and *application*. The first study (*accuracy*) examined alternative methods of herbage mass sampling using a rising plate meter and showed that a marginally less accurate protocol can reduce labour time by 51.2% while still providing information of an acceptable quality to support grazing management decisions. The second study (*impact*) uncovered a previously unknown association between a lamb's weight at weaning and its subsequent carcass quality and quantified the farm-scale economic benefits of interventions to improve lamb weights at early stages of their lives. Finally, to identify measurable indicators of animal performance that provide the greatest potential benefit to farmers, the third study (*application*) developed a computational framework to assign economic values to individual metrics as well as their combinations, rank them accordingly and compile actionable benchmarks for effective real-time interventions. Collectively, the findings presented here demonstrate the positive benefit of on-farm monitoring and offer a scientifically robust yet practically implementable method for identifying what to measure and what need not be measured on sheep farms.

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## Author’s declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

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# List of acronyms

AHDB: Agriculture and Horticulture Development Board

AMSL: above mean sea level

ANOVA: analysis of variance

ASF: animal source foods

BCS: body condition score

BPS: Basic Payment Scheme

CAP: Common Agricultural Policy

CIEL: Centre for Innovation Excellence in Livestock

CS: conformation score

CSH: compressed sward height

CT: computer tomography

DEFRA: Department for Environment, Food and Rural Affairs

DM: dry matter

EEC: European Economic Community

ELMs: environmental land management schemes

EU: European Union

FAO: Food and Agriculture Organisation of the United Nations

FC: fat class

FYM: farmyard manure

GHG: greenhouse gas

GPS: global positioning system

HM: herbage mass

IPCC: Intergovernmental Panel on Climate Change

KPI: key performance indicator

LMIC: low- and middle-income countries

LU: livestock unit

MHIC: middle- and high-income countries

NWFP: North-Wyke Farm Platform

NSA: National Sheep Association

NZ: New Zealand

PCA: principal component analysis

RPM: rising plate meter

UAV: unmanned aerial vehicle

UK: United Kingdom

US: United States

VIA: video image analysis

# Publications resulting from this PhD research

## Peer reviewed journal articles (published)

Jones AG, Takahashi T, Fleming H, Griffith BA, Harris P and Lee MRF 2021. Using a lamb's early-life liveweight as a predictor of carcass quality. *Animal* 15, 100018.

Jones AG, Fleming H, Griffith BA, Takahashi T, Lee MRF and Harris P 2021. Data to identify key drivers of animal growth and carcass quality for temperate lowland sheep production systems. *Data in Brief* 35, 106977.

Part of Chapter 4 is based on these publications with the co-authors' permissions.

## Peer reviewed journal articles (manuscripts submitted)

Jones AG, Takahashi T, McConnell DA, Huson KM, Lee MRF and Harris P 2021. Accuracy-cost trade-off of grassland monitoring by rising plate meters. *Precision Agriculture*.

Part of Chapter 3 is based on this publication with the co-authors' permissions.

Jones AG, Takahashi T, Fleming H, Griffith BA, Harris P and Lee MRF 2021. Quantifying the value of on-farm measurements to inform the selection of key performance indicators for livestock production systems. *Scientific Reports.*

Part of Chapter 5 is based on this publication with the co-authors' permissions.

## Conference contributions

Jones, A.G., Takahashi, T., Fleming, H., Griffith, B.A., Harris, P. & Lee, M.R.F. Redefining Key Performance Indicators for livestock production systems: what is the value of information? *British Society of Animal Science Conference 2021.* Online.

Jones, A.G., Takahashi, T., Harris, P. & Lee, M.R.F. A novel method to minimise labour costs of herbage monitoring based on spatial heterogeneity. *71st Annual meeting of the European Federation of Animal Science 2020.* Online.

Jones, A.G., Takahashi, T., Fleming, H., Griffith, B.A., Harris, P. & Lee, M.R.F. No such thing as a 'strong' lamb? Ewes' influence on pre- and post-weaning animal growth. *71st Annual meeting of the European Federation of Animal Science 2020.* Online.

Jones, A.G., Takahashi, T., Fleming, H., Griffith, B.A., Harris, P. & Lee, M.R.F. Redefining Key Performance Indicators for sheep production systems. *British Society of Animal Science Conference 2020.* Abstract published online (Conference cancelled due to Covid-19).

Jones, A.G., Takahashi, T., Harris, P. & Lee, M.R.F. Labour saving associated with alternative Rising Plate Meter sampling techniques. *British Society of Animal Science Conference 2020.* Abstract published online (Conference cancelled due to Covid-19).

Jones, A.G., Takahashi, T., Fleming, H., Griffith, B.A., Harris, P. & Lee, M.R.F. Redefining Key Performance Indicators for sheep production systems. *70$^{th}$ Annual meeting of the European Federation of Animal Science 2019.* Ghent, Belgium.

Jones, A.G., Takahashi, T., Fleming, H., Griffith, B.A., Harris, P. & Lee, M.R.F. Pre-weaning and post-weaning growth performances of lambs may be uncorrelated. *British Society of Animal Science Conference 2019.* Edinburgh, Scotland.

Jones, A.G., Takahashi, T., Fleming, H., Griffith, B.A., Harris, P. & Lee, M.R.F. Using pre-weaning lamb liveweight as a predictor of carcass quality. *British Society of Animal Science Conference 2019.* Edinburgh, Scotland.

Takahashi, T., Harris, P., McAuliffe, G.A., Jones, A.G. & Lee, M.R.F. Low-resolution soil sampling may provide no useful information to grazing farms. *British Society of Animal Science Conference 2019.* Edinburgh, Scotland.

# Chapter 1. Introduction

## 1.1. Challenges facing agriculture

The world population is expected to reach 9.15 billion people by 2050, according to current growth trajectories (van Kernebeek et al., 2016). It is predicted that this growth will lead to overall global food demand increasing by 60%, and this impact will likely be felt most acutely in the regions of the world that are anticipated to experience the sharpest population growth – the majority of which already experience inadequate food consumption and high levels of undernourishment (Alexandratos and Bruinsma, 2012). These increasing food demands will drive substantial pressure on future land-use, further aggravated by land degradation (Stringer, 2008), increasing demands for biofuels (Searchinger et al., 2008), housing, and infrastructure (Grimm et al., 2008). However, with agricultural land already accounting for ~38% of global land surface area (Foley et al., 2005), further areal expansion will not be able to provide a socially acceptable way of sustainably meeting increasing food demands.

Compounding the need for increased food production, agriculture is known to be a significant driver of many environmental threats. These threats include biodiversity loss (Vitousek et al., 1997; Phalan et al., 2011), degradation of marine, freshwater and terrestrial ecosystems through nutrient run-off (Power, 2010) and sedimentation of waterways (Zhang et al., 2007). Perhaps most crucially these threats also include climate change, as agriculture accounts for 10-12% of total anthropogenic GHG emissions (Burney et al., 2010). Future agricultural production will therefore need to provide an increased quantity of nutrient-rich foods but with a reduced environmental impact (Foley et al., 2011).

In addition to being one of the key drivers *of* climate change, the issues discussed above are likely to interact *with* climate change in several ways. In dry and tropical regions, even a slight temperature increase is predicted to reduce crop and pasture yields, and, although a moderate increase in temperature is predicted to increase yields in mid- to high-latitude regions (Olesen and Bindi, 2002), any further warming beyond this will have increasingly negative impacts in all regions (IPCC, 2007). Increased variability of rainfall is anticipated to increase the risk of flood and, combined with higher temperatures, the risk of drought particularly in some of the most food-insecure regions such as sub-Saharan Africa (Power, 2010). Alongside these direct impacts, events such as conflict (Hsiang et al., 2013), fire (Bowman et al., 2009) and disease outbreak (Middendorf et al., 2021; Rasul, 2021; The Andersons Centre, 2021) are all likely to increase with climate change, and can cause regional shocks on food security (Godfray et al., 2010).

Future food security not only requires a greater quantity of food to be produced with a reduced environmental impact, but also requires different types of food in order to meet nutritional demands. The increasingly wealthy global population is driving the demand for more nutrient rich foods, most notably animal source foods (ASF) such as dairy, fish and meat, all of which add further pressure to current food supply systems (Godfray et al., 2010). The role of livestock within sustainable future food systems must therefore be carefully considered.

### 1.2. The role of livestock within future food production

The current livestock sector uses ~70% of all agricultural land and, globally, animal source foods contribute 15% of total food energy and 25% of dietary protein (FAO, 2009). In recent years, ASF have been perceived in an increasingly negative light due to the substantial environmental impact of livestock (Steinfeld, 2006), and its contribution to unhealthy diets when consumed in excess (Willett et al., 2019a). However, ASF provide a variety of micronutrients which are difficult or expensive to obtain in adequate quantities from plant source foods alone (Murphy and Allen, 2003), particularly in low- and middle-income countries (LMICs) (Randolph et al., 2007; Hirvonen et al., 2020), where undernutrition and micronutrient deficiencies already have numerous and far-reaching health implications (Ramakrishnan, 2002; Adesogan et al., 2020). Furthermore, even within middle- to high-income countries (MHICs), diets which include ASF have been shown to be the most cost-effective way of successfully achieving a nutritionally adequate diet (White and Hall, 2017; Chungchunlam et al., 2020). Livestock's contribution to human society also extends beyond the provision of ASF. Within many MHICs livestock are considered major contributors to the national economy and support rural communities (The Rural Business School, 2018; CIEL, 2020; Rose et al., 2021). Within LMICs livestock often have a more diverse role, and are kept for reasons including: producing food, generating income, providing manure, producing draught power, serving as financial instruments and enhancing social status (Upton, 2004; Randolph et al., 2007; Herrero et al., 2013a).

A substantial proportion of the world's meat, and the majority of the world's milk come from ruminant animals, predominantly cattle, sheep and goats (Eisler et al., 2014). Ruminants have a unique digestive system which produces the potent GHG methane as a by-product of enteric fermentation (Gerber et al., 2013). Although the relative long-term impact of short-lived gases such as methane is currently undergoing debate (Cain et al., 2019; IPCC, 2019; Lynch et al., 2020) and recent advances in methane mitigating feed additives have shown substantial promise (Roque et al., 2021), in conjunction with a comparatively low feed conversion efficiency and substantial land-use requirements

(Herrero et al., 2013b) the environmental impact of ruminants has justifiably led to intense scrutiny of their role within sustainable food systems (Steinfeld, 2006; Willett et al., 2019a). Although their digestive system is the source of much of their environmental impact, the rumen is both a blessing and a curse as it allows ruminants to utilise land areas and food types unsuitable for direct human consumption (Wilkinson, 2011; Röös et al., 2016; Garnett et al., 2017). A series of forestomaches (the largest of which is the rumen) allows ruminants to break down fibrous plant materials into usable calories and microbial protein. This enables the grazing of marginal areas, such as mountainsides and low-lying wet grasslands, thus creating nutritional value from grasslands by converting grass into milk and meat (van Zanten et al., 2018), and in-turn reserving more accessible agricultural areas for the production of human-edible crops (Eisler et al., 2014; van Zanten et al., 2016). In addition to the use of human-inedible by-products from the food system (Wilkinson and Lee, 2018; van Zanten et al., 2019), this indicates that ruminants are likely to have a crucial role in ensuring optimal land-use for providing a healthy and sustainable diet (van Kernebeek et al., 2016).

Aside from their direct contribution to a sustainable and healthy diet, pasture-based ruminant systems also have a broader influence on food production in general, due to their impact on soil health (Rivero et al., 2021). Since the industrial revolution, intensive agricultural activities have driven the degradation of soils, and is considered to be the most destructive human impact on soil sustainability (Amundson et al., 2015). Soil erosion and its negative impact on soil health limit the food production capacity of land, and if current soil health trajectories continue, there will likely be grave impacts on food security, ecosystem services and climate sustainability (McBratney et al., 2014; FAO, 2015). When appropriately managed, ruminants are able to play a role in reversing this decline; grazing livestock provide vital nutrients to the soil (Garnett, 2009), can increase fertility and biological activity

(Fließbach et al., 2007), increase carbon sequestration (Teague et al., 2016; Garnett et al., 2017) and regenerate soil fertility by facilitating nutrient cycling (Broom et al., 2013).

### 1.3. The role of small ruminants within future food production

Whilst cattle are by far the most dominant ruminant livestock species globally (Gerber et al., 2015), small ruminants, such as goats and sheep, also have a crucial role to play in sustainable agriculture. In the context of a changing climate, small ruminants are likely to prove more versatile than larger ruminants as their general physiology means they are more resistant to heat stress (Pardo and del Prado, 2020) and their agility and hardiness allows them to browse and graze in more extreme marginal areas (Aich and Waterhouse, 1999). Particularly within the resource-limited arid and tropical areas which characterise many LMICs, small ruminants are widely considered to better meet the needs for sustainable food security and economic diversification than larger ruminants due to their manageable size, low capital investment cost and relatively low nutrient requirements (Sargison, 2020).

In more temperate agricultural regions more typical of many MHICs, for example the United Kingdom (UK) where the present study was conducted, sheep are the most dominant small ruminant species and have substantial local importance, both economically and culturally (Caroprese et al., 2015; Ross et al., 2016; Morgan-Davies et al., 2017a). Within these areas, sheep farming can contribute to sustainable agriculture mainly via two pathways. Firstly, sheep are used to graze hill and upland regions unsuitable for cattle (Watson and More, 1945), thus converting forage into human edible protein in marginal areas otherwise unsuitable for human food production (Eisler et al., 2014), helping to support biodiversity and ecosystem services (O'rourke et al., 2012; Austrheim et al., 2016) and maintaining grassland areas for the purpose of tourism and recreation (Lombardi, 2005; Thompson, 2009). Secondly, sheep are often grazed on managed lowland pastures where they are most often used in combination with cattle, or alternatively on mixed farms and within crop rotations (Aich and Waterhouse, 1999; Aquino Alves et al., 2020; Sargison, 2020). When used in a multi-species pasture rotation, the inclusion of sheep has the potential to help regenerate land and improve soil health, while producing high quality protein (Rowntree et al., 2020). Farms which specifically graze both sheep and cattle have increased management flexibility and are more resilient to change, as they are able to preferentially graze one species while maintaining grazing pressure for the other. As economic conditions change farms are also easily able to alter their mix of sheep and cattle to suit market demand (Morris, 2013). Furthermore, when cattle and sheep are managed within the same grazing platform, it can drive rapid improvements in soil physical properties when compared to pastures grazed by cattle alone, which could potentially provide a simple way of improving the provision of water flow regulation and other ecosystem services (Jordon, 2020).

Sheep are thus likely to play a key part in the development of sustainable food systems. However, due to the aforementioned environmental and resource use efficiency issues associated with ruminant production, sheep can only contribute in a positive manner if they are managed in a way which supports maximum production efficiency.

### 1.4. The UK sheep sector

Domesticated sheep are thought to have arrived in the UK around 3000 B.C. when Neolithic settlers crossed the English channel from mainland Europe (Ryder, 1964). Sheep numbers were even described in the Domesday survey (soon after the Norman Conquest), during which time there were more sheep in Britain than all other livestock combined. Since their introduction sheep have played a considerable role in the development of UK agriculture, providing three major products: meat, wool and milk, although the majority of their development and breeding has taken place since around 1800 (Owen, 1976). The sheep which first arrived in the UK are thought to have resembled some of the primitive sheep breeds still present today (such as the Soay, Boreray and St Kilda breeds), however over the last two centuries intensive breeding practices and the introduction of foreign breeds have led to the 106 breeds and crosses (59 of which are considered native) present in the UK today (Carson et al., 2008; Pollott, 2014). Much of the reason for this breed diversity is through adaptation to the large variety of environments and habitats present within the country, which over time has led to a complex 'stratified' cross-breeding structure (Owen, 1976).

The stratified sheep system is unique to the UK, and is divided into three tiers: hill, upland, and lowland (**Figure 1.1.**). Although this system is complex and dynamic, it is well summarised below by Rodriguez-Ledesma et al., (2011):

> Typically, this involves low fertility, hardy Hill ewes being bred pure on the hills then drafted to easier conditions in the uplands for one or two final crops, where they are mated to a prolific long-wool crossing sire – typically a Bluefaced Leicester. The resulting ewe lambs (called Mules) are sold to lowland farmers where, over 4–5 crops, they are mated to meaty Terminal Sires to produce finished lambs.

This structure is essential to the productivity of the UK sheep sector and utilises the traits inherent to the different breeds present, however there are a number of risks associated with this system, for example the importance of each individual level to the stability of the whole sector (National Sheep Association, 2021), and the risk of disease transmission caused by its dynamic structure (Green et al., 2006).

The UK national flock is the largest in Europe, consisting of 33,781,000 head of sheep and lambs as of June 2018 (AHDB, 2019a). Although in many regions of the world sheep farming is focused on either the production of wool (Dart et al., 2011) or milk (Carta et al., 2009), sheep in the UK are predominantly used for the seasonal production of meat (mutton and lamb meat) (Croston and Pollott, 1994), of which the UK produces around 300,000 tonnes each year. Around a third of this amount is exported, with approximately the same amount imported, giving the total UK sheep meat consumption at around 295,000 tonnes (AHDB, 2019a). Through live- and dead-weight sales, meat exports, and processing and packing, the sheep sector directly contributes in excess of £2.5 billion to the UK economy, with a further £291 million through employment, involving 34,000 jobs directly linked to sheep farming and a further 111,000 in allied industries (The Rural Business School, 2018). At the same time, sheep farming in the UK has been heavily supported by agricultural subsidies since the second world war, particularly in hill and upland areas (Morgan-Davies et al., 2012). Since the UK joined the European Economic Community (EEC) in 1973 (Burkitt and Baimbridge, 1990), this support has been provided in various forms by the Common Agricultural Policy (CAP), most recently in the form of the Basic Payment Scheme (BPS) (Barnes et al., 2016; Ciliberti et al., 2018), and it is widely accepted that without financial support many sheep farms would be unprofitable and likely to collapse (Helm, 2017; Hubbard et al., 2018).

On the 23rd of June 2016 the UK referendum on European Union (EU) membership resulted in 51.9% of voters voting in favour of leaving the EU (The Electoral Commission, 2016). The UK's departure from the EU will require a re-negotiation of agricultural trade deals, which are anticipated to have a negative impact on the income of UK sheep farms (Patton et al., 2017; Wallace and Scott, 2017; Hubbard et al., 2018), and will also see an exit from CAP's support framework and a phasing out of direct payments from January 2021 (DEFRA, 2020a). Instead, financial support will be offered through Environmental Land Management schemes (ELMs) which are due to replace both BPS and Countryside Stewardship funding (DEFRA, 2018). These renewed payments are intended to drive an 'agricultural transition' towards improved economic, social, and environmental sustainability of farming in the UK. However as sheep farming in the UK has long been associated with low profitability (Lima et al., 2020) attributable to low production efficiency when compared to the other livestock sectors (Cutress, 2020), in order for sheep production to positively contribute towards these goals and remain economically viable, substantial improvements in production efficiency are vital.

### 1.5. Improving the efficiency of UK sheep production

UK sheep farming is known to be extraordinarily varied, not only in terms of breed, production and land use, but also in terms of physical and financial performance between flocks (Kilkenny and Read, 1974; The Rural Business School, 2018). Improving the overall production efficiency of the sector by reducing the yield-gap present on low-performing farms is key to improving the profitability (Croston and Pollott, 1994) and reducing the environmental impact of the sector as a whole (Henriksson et al., 2011; Jones et al., 2013, 2014). Although much of the variation in production efficiency between farms can be explained by biophysical, climactic or socioeconomic conditions, productivity is often limited by management (Foley et al., 2011). It is often considered that successful farm business management comprises two main elements: planning (making decisions that affect the future operation of the business) and control (monitoring the progress of decisions and taking any necessary corrective actions). Both of these elements are reliant on a comprehensive understanding of the processes which occur on the farm, and monitoring both the financial and physical performance of these processes is an essential component of supporting management decisions to improve production efficiency (Soffe and Lobley, 2021). This argument is supported by various studies: for example, a study conducted by Lima et al. (2019) investigated factors with the largest and most reliable associations with lamb-derived revenue on sheep farms. The study identified six factors with a substantive positive impact on both lamb-derived revenue per acre and per ewe, factors which were deemed the most important areas to consider for intervention. These were: farmers receiving an education above secondary school level, increasing stocking rates, using infertility as a reason for culling ewes, managing lameness in ewes, and conducting BCS in early lactation and at weaning. Keeping good farm records in particular was identified as crucial for maximising the value of these six factors, as interventions involving culling decisions and BCS monitoring, for example, would be impossible without a good level of performance monitoring. Similarly, in a survey of grassland farmers in Northern Ireland, McConnell et al. (2020) reported that performance monitoring remains limited with only 13.5% respondents measuring and recording grass production on their farm. However, the farmers who did measure recorded annual grassland yields 1.6 times higher than the industry average (7.9t DM/ha), demonstrating the value of performance monitoring for supporting increased productivity.

The UK sheep sector is known to have an exceptionally low level of performance monitoring and record keeping, with many farmers unaware of where money is made or lost within their enterprise (Kaler and Green, 2013). Although this low-level of performance monitoring is widely accepted to be true amongst industry stakeholders, there is limited evidence to formally support this claim at the national scale. Motivated by this gap in information, the author conducted an informal online survey of 475 sheep farmers associated with the

National Sheep Association (NSA) during January and February of 2021 to test these assumptions. The survey focused on questions related to on-farm record keeping practices of the respondent, including weighing and condition scoring of ewes and lambs, pasture sampling, soil sampling and forage sampling. While the demographic of NSA members is undisclosed and in any case unlikely to align perfectly with the overall sheep farmer population in the UK, the results provide a valuable insight into current performance monitoring practices. For example, although 89% of respondents claimed to own a usable sheep weighing crate, 56% never weighed their ewes and, out of the respondents who did, 39% did not record this information (presumably using the current weight for drafting purposes only), thus rendering the information unusable for long-term decision making (**Table 1.1**). Although condition scoring of ewes was more common (83% claimed to score the physical condition on a scale of 1-5), again only a small proportion (21%) of these farmers recorded the information either digitally or on paper. Above all, the most notable response referred to the measurement of pasture cover, with only 15% of respondents formally measuring pasture cover on their farm and the remainder judging by eye only, a method which is long established to be often inaccurate and with low repeatability (Stockdale, 1984).

Although these results help to assess the present situation surrounding performance monitoring on UK sheep farms, positive change can only occur if the reasons behind this low level of performance monitoring are also elucidated. To investigate this, respondents who answered that they did not record a particular type of information were then asked for the main justification for not doing so. Across all types of information, the most commonly selected reason was the identical – ‘Current management practices are adequate’ (**Table 1.2**). A further follow-up question was then asked to explore whether they would be willing to record the relevant information if the resultant management practices increased income by a certain amount. Responses to this question were relatively divided, with between ~55-65% indicating that their ‘decision was not financially motivated’, and the remainder indicating that they would be willing to measure if there was a tangible financial benefit (**Table 1.3**). These findings indicate that farmers can broadly be divided into two groups. Between them, those in the first group consider their management practices to be already optimal and thus do not accept that an increase in performance monitoring can provide a benefit. On the other hand, those in the second group accept that an increase in performance monitoring could be beneficial but would only be willing to implement this practice if there is a demonstrable financial benefit. Thus, to drive an increase in record keeping and performance monitoring practices across UK sheep farmers, two similar, but different approaches are required. For the first group, the overall benefit and value of performance monitoring needs to be demonstrated in order to refute the ‘myth’ that it is unable to provide a benefit. For the second group, a greater proportion of whom become more willing to engage in on-farm measurements when the financial benefit becomes higher (**Table 1.3)**, an additional mechanism is required to identify on-farm metrics that provide the greatest value.

Finally, while low farmer motivation to record information is primarily driven by a lack of perceived benefit and ambiguity surrounding what information should be recorded, it is worthwhile noting that it has been further exacerbated by an underlying economic factor and in particular the sector’s historic reliance on agricultural subsidy payments outlined in Section 1.4. The guaranteed income provided by BPS reduces the need for sheep farmers to keep records and understand where flock income and expenditures arise, as any potential increase in income provided via good record keeping is relatively small when compared to the value of BPS (Kaler and Green, 2013).

## 1.6. The aims and structure of this thesis

Combined together, the low level of performance monitoring on UK sheep farms can be attributable to three elements; firstly, there is a low financial incentive to record information due to the scale of economic support provided by subsidies; secondly, a large proportion of farmers either fail to acknowledge that recording information can provide a benefit, or perceive little economic benefit in recording information on their particular farms; and finally there is no clear guidance around exactly what and how much information should be recorded in order to support management decisions which will actually result in a tangible economic benefit.

To encourage the uptake of record keeping there is thus a crucial need to demonstrate the value and benefit of using on-farm information to influence changes in management, as farmers are unlikely to allocate resources (be they labour, capital or land) towards tasks with a low level of perceived benefit (Wallace and Moss, 2002; Hyland et al., 2018). In addition, there is a need to identify exactly what information is able to provide the greatest tangible benefit in order to reduce the ambiguity around their purpose. It is hypothesised, however, that not all variables are of equal value and depending on the specific farming system involved there is substantial variation in how beneficial the measurement of each metric can potentially be.

Within this thesis the potential benefit of measured information is conceptually separated into three aspects : *accuracy*, *impact,* and *application*. 'Accuracy' represents the link between an individual metric and each target outcome (e.g. the link between current lamb daily liveweight gain and lamb finishing age) and is broadly determined by the strength of causal relationship. ‘Impact’ characterises the relative contribution of each individual outcome to the overall performance of the enterprise (e.g. the effect of a shortened finishing age on farm profitability). Finally, ‘application’ quantifies how easily and cost-effectively the management changes driven by a metric can be used to influence tangible change on a farm (e.g. the cost and viability of improving current lamb daily liveweight gain). Following a brief chapter introducing the study site (**Chapter 2**), three studies that constitute the main chapters of the thesis will examine each of these aspects in greater detail. Their contents are outlined below:

**Chapter 3 - Accuracy-cost trade-off of grassland monitoring by rising plate meters.** Due largely to high labour requirement throughout the season, the Rising Plate Meter (RPM) is currently underused in the UK. A marginally less accurate but substantially faster method could encourage the uptake of the RPM, and in turn improve the efficiency of grassland production. This study investigates the **accuracy** aspect of a performance indicator (herbage mass) by examining alternative rising plate meter sampling methods, and specifically investigates accuracy-cost trade-offs to ask the question of ‘how accurate must information be to still provide a benefit?’

**Chapter 4** - **Using a lamb's early-life liveweight as a predictor of carcass quality.** Profitability of UK sheep farms is dictated by the value of slaughter-lamb sales, which itself is determined by the weight and quality of each lamb’s carcass. The ability to predict carcass quality at an early stage of lamb growth would provide an opportunity for producers to apply interventions which could have a substantial impact on overall farm income. This study therefore investigates the **impact** aspect of a performance indicator by examining the relationship between lamb weight at weaning (a key intervention point) and their subsequent carcass quality and examines the farm-scale economic benefits associated with interventions to improve early-life lamb weight.

**Chapter 5 - Quantifying the value of on-farm measurements to inform the selection of key performance indicators for livestock production systems.** Although the term ‘key performance indicators’ (KPIs) is in common usage within the UK livestock industry, their overabundance and lack of clearly defined application methods has disincentivised many farmers to collect information beyond what is absolutely necessary. This final substantial chapter investigates the **application** aspect of potential information benefit by developing a framework for ranking and attributing economic values to metrics currently in use and defining actionable benchmarks to enable interventions based on this information within a commercial setting.

**Table 1.1.** Management practices of UK sheep farmers: (1) Measurement of on-farm metrics

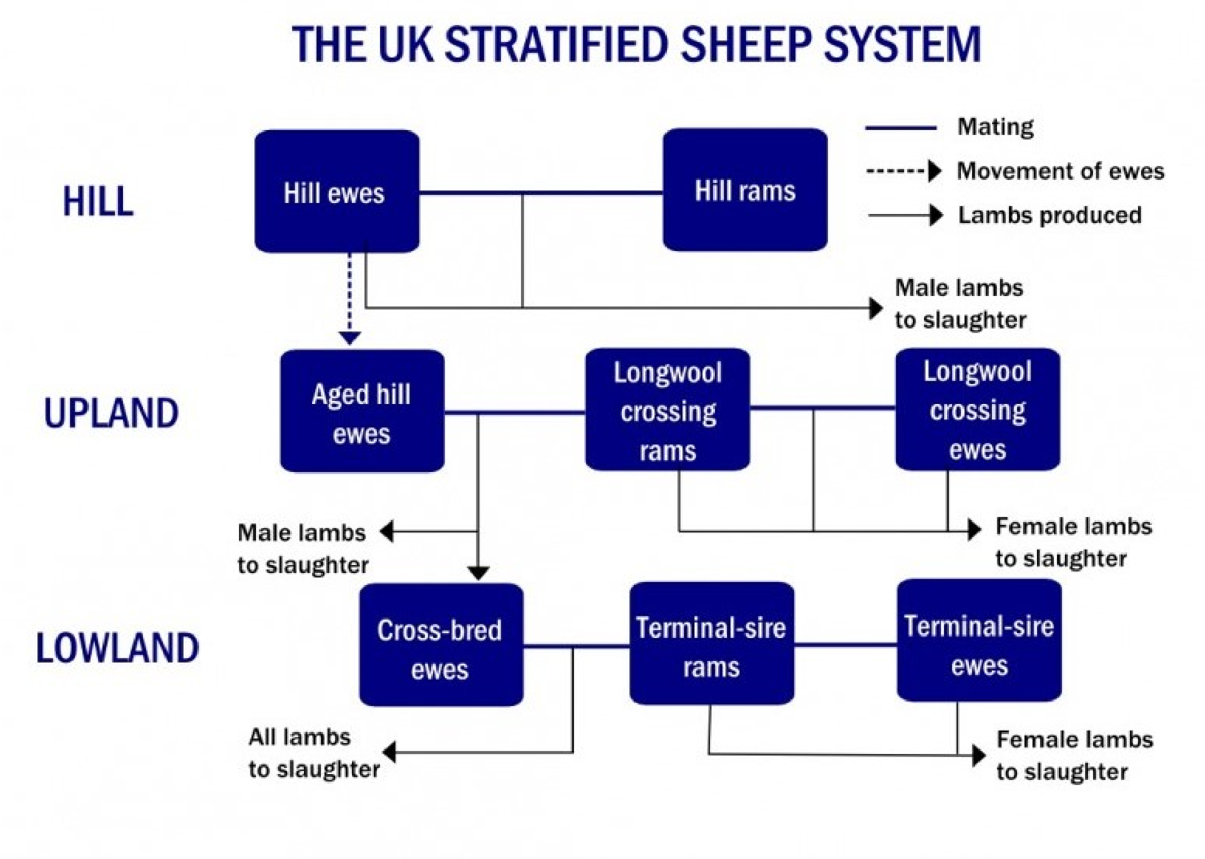
| | Yes | No | n |
|---|---|---|---|
| Do you own a usable sheep weighing crate? | 89.2% | 10.8% | 231 |
| Do you measure the weight of your ewes? | 43.6% | 56.4% | 413 |
| If you do measure the weight of your ewes, do you record it? (either on paper or digitally) | 60.8% | 39.2% | 176 |
| Do you Body Condition Score your ewes? (assess their physical condition on a scale of 1-5) | 82.8% | 17.2% | 407 |
| If you do measure the condition score of your ewes, do you record it? (either on paper or digitally) | 21.2% | 78.8% | 335 |
| Do you measure the weight of your lambs? | 85.4% | 14.6% | 404 |
| If you measure the weight of your lambs, do you record it? (either on paper or digitally) | 63.2% | 36.8% | 345 |
| Do you measure pasture cover on your farm? | 14.6% | 85.4% | 397 |

**Table 1.2.** Management practices of UK sheep farmers: (2) Justification for not taking measurements

| | What is the main reason you do not measure this? | | | | | | |
|---|---|---|---|---|---|---|---|
| | Of no benefit | Time consuming | Expensive | Physically demanding | Current management practices adequate | Other | n |
| Ewe weight | 21.2% | 13.0% | 1.7% | 3.9% | 49.8% | 10.4% | 231 |
| Ewe Body Condition Score | 12.7% | 12.7% | 0.0% | 2.8% | 54.9% | 16.9% | 71 |
| Lamb weight | 17.0% | 17.0% | 3.4% | 1.7% | 32.2% | 28.8% | 59 |
| Lamb Body Condition Score | 20.7% | 10.4% | 0.0% | 1.2% | 50.6% | 17.0% | 164 |
| Pasture cover | 9.4% | 10.3% | 2.7% | 0.6% | 59.0% | 18.0% | 339 |

**Table 1.3.** Management practices of UK sheep farmers: (3) Financial motivation for monitoring

| | Would you be willing to record this information if the resultant management practices increased income by the following amounts | | | | | |
|---|---|---|---|---|---|---|
| | £1/lamb | £3/lamb | £5/lamb | £10/lamb | Decision is not financially motivated | n |
| Ewe Body Condition Score | 5.7% | 8.6% | 14.3% | 8.6% | 62.9% | 70 |
| Lamb weight | 6.9% | 15.5% | 17.2% | 6.9% | 53.5% | 58 |
| | £10/ha | £30/ha | £50/ha | £100/ha | Decision is not financially motivated | n |
| Pasture cover | 8.9% | 18.2% | 11.9% | 6.9% | 54.2% | 336 |




645 **Figure 1.1.** The UK stratified sheep system (*Source*: National Sheep Association 2021).

# Chapter 2. The North Wyke Farm Platform

The studies described within subsequent chapters were conducted at the North Wyke Farm Platform (NWFP) or using data previously collected from the NWFP. To reduce duplication this chapter provides a basic description of the site, pasture management and livestock management that are common across all chapters.

## 2.1. Site description

The NWFP was constructed in 2010 (Orr et al., 2016) near Okehampton in Devon, UK (50º46’10”N, 3º54’05”W) and comprises three hydrologically isolated enterprises (21 ha each) known locally as ‘farmlets’. Designed to test the sustainability (Carswell et al., 2019) and productivity of contrasting temperate beef and sheep systems at the farm scale (Orr et al., 2019), each farmlet operates under a different management strategy which, until 2019, consisted of reseeded grass monoculture, reseeded grass/legume mix and non-reseeded (permanent) pasture, known as ‘Red’, ‘Blue’ and ‘Green’ farmlet respectively (**Figure 2.1**). Red farmlet was recently converted to an arable enterprise from a reseeded grass monoculture to evaluate the feasibility of non-livestock production systems in a traditionally grassland landscape, however data from periods after this conversion were not used for this thesis.

The site is located in a lowland region (126-180m AMSL) of South West England, with the land sloping away to the west and east towards the River Taw and one of its tributaries, respectively. The soil on the site predominantly belongs to two similar series, Hallsworth and Halstow (Avery, 1980), combining a moderately stony clay loam top layer (~36% clay) overlying a mottled stony clay sub-layer (~60% clay). It receives a large and consistent amount of rainfall, characteristic of grassland regions in the South West of England, with a mean annual precipitation of 1030mm over a 35-year period between 1984 to 2019. Over this period, the interquartile ranges for minimum and maximum daily temperatures were 3.6–10.4°C and 9.8–17.4°C, respectively. Further details of the weather and soil of the site are available elsewhere (Orr et al., 2016; McAuliffe et al., 2020; Lee et al., 2021).

### 2.2. Livestock management

Each livestock farmlet of the NWFP supports its own herd of 30 finishing cattle, which enter the platform at the point of weaning in autumn (McAuliffe et al., 2018a), and a mixed age flock (2–8 years) of Suffolk x Mule ewes, mated to Charollais rams over a 6-week period in October and November each year. Cattle are housed from October to April to avoid degradation of soil structure through livestock poaching, while sheep are housed between January to April over the lambing period. During this time ewes were initially fed a grass silage-based ration, with multiple-bearing ewes later supplemented with concentrates for up to six weeks prior to lambing. For the remainder of the year, livestock are grazed under continuous variable stocking to represent the most common grazing strategy in the UK (Genever and Buckingham, 2016; Allen et al., 2018) and rotated between seven paddocks based on herbage mass (HM) measurements (McAuliffe et al., 2020).

Over the nine-year period between 2011-2019, the sheep flock produced an average of 2.01 lambs per year, with lambs born indoors in March/April and turned out to pasture at 72 hours postpartum. Ewes were checked for colostrum production immediately postpartum, and lambs from ewes providing an insufficient amount were supplemented from a donor ewe or with powdered colostrum. Lambs were reared as either singles or twins, with one of the triplet-born lambs either cross-fostered onto a single-rearing ewe or artificially reared (with milk replacer). In the latter case, these lambs were taken off the NWFP and thus do not contribute to the dataset. Male lambs were castrated at 24 hours post-lambing. Once at pasture neither ewes nor lambs received supplementary feed. Ewes and lambs were initially placed on the same pasture and subsequently split into separate enclosures at weaning, which occurred at 13 weeks from the average lambing date.

The liveweight of lambs was recorded at weaning and every two weeks thereafter until finishing, and when weights at key growth stages (such as 4-week and 8-week measurements) were not taken on the exact day, a linear adjustment was made to estimate the corresponding weight to ensure inter-animal comparability. Upon reaching a target liveweight of ~40kg lambs were screened for carcass quality (musculature and fat cover) via handling at the loin, dock, rib, and breast, with those deemed to meet the standard industry criteria separated for slaughter. Over the combined study period from 2011-2019, lambs were finished at an average of 170 days, with an average carcass weight of 44.5kg. Post-slaughter, information on cold carcass weight, carcass quality and current carcass price were obtained from the abattoir. For dams, bodyweight and body condition score (BCS) (Russel et al., 1969) were recorded at three key stages in the production cycle: tupping, lambing and weaning. Both ewes and lambs were weighed individually on a Border Software 3-way drafting weigh crate, equipped with Tru-Test MP600 load bars, a Tru-Test EziWeigh7i weighing head and a Tru-Test SRS2 stick-reader. Different subsets of these data were used for studies reported within this thesis.

### 2.3. Grazing management

Prior to the construction of the NWFP no fields had been reseeded for at least 30 years and were therefore all considered to be permanent pasture. From 2014 onwards (and thus during the study period of all subsequent chapters) two of these swards were reseeded with modern cultivars (Takahashi et al., 2018). The different swards used within each farmlet are described in full by Orr et al. (2016), but are briefly summarised below.

1. ***Blue farmlet, legumes.*** Sward reseeded using perennial ryegrass (*Lolium perenne* L. Aber®Magic) and white clover (*Trifolium repens* L. Aber®Herald) mixtures.
2. ***Red farmlet, planned reseeding.*** Sward reseeded with a high-sugar perennial ryegrass monoculture (*Lolium perenne* L. Aber®Magic).
3. ***Green farmlet, permanent pasture.*** Sward maintained as permanent pasture, with species composition dominated (>60%) by perennial ryegrass (*Lolium perenne*).

To follow the most common local practice, animals were rotated between seven paddocks within a single enterprise based on pasture cover measurements. The target dry matter coverage was set at 2000-2500 kg DM/ha for cattle, and 1500-2000 kg DM/ha for sheep during the majority of the grazing season and 1800-2500 kg DM/ha during the period leading up to ewe tupping in the autumn (Penning et al., 1995). Once HM fell below the target range, stocking density was reduced by allowing animals access to additional grazing area or by moving animals to another paddock if available. When HM became too high, on the other hand, stocking density was increased by fencing off a proportion of the grazing area, which was then cut for silage or topped.

Decisions on silage production were dictated by pasture requirements for grazing, and as such the area and frequency of harvest were back-calculated from the balance between herbage growth rates and expected animal intake before housing. Due to the biological N fixation abilities of clover-based systems, fields within the blue farmlet only received inorganic N fertiliser during periods of exceptionally slow growth. Depending on weather and soil conditions, grazed swards within the red and green farmlets received a maximum of five applications of synthetic N fertiliser, at a rate of 40 kg N/ha in the form of ammonium nitrate, in monthly intervals from March to July. Green and red fields designated for silage received compound fertiliser (N, P, K, S) at a rate of 80kg N/ha, 14kg of P/ha and 24kg of S/ha in March, plus an additional 40 kg N/ha of ammonium nitrate in April. Following silage cut and removal, farmyard manure (FYM) collected from the previous winter housing period was applied at a typical rate of 19 t/ha (157 kg N/ha), to all fields subsequently to be grazed later in the season.

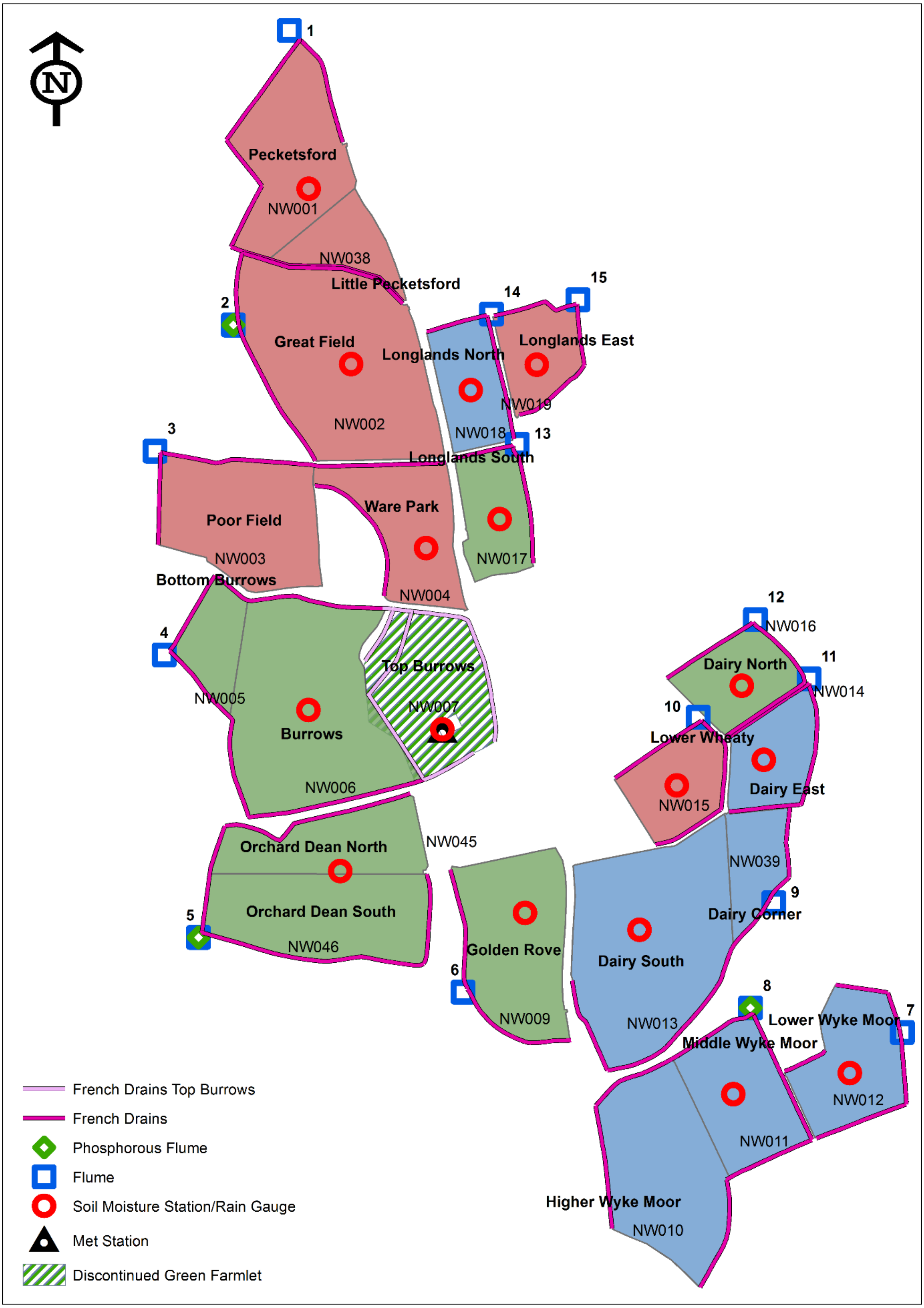



**Figure 2.1.** The North Wyke Farm Platform. As of July 2019 (pre-conversion of Red farmlet). Colour coding of farmlets corresponds to farming system, as described above.

# Chapter 3. Accuracy-cost trade-off of grassland monitoring by rising plate meters

## Summary

Production efficiency of pasture-based livestock production systems is primarily driven by the internal level of pasture utilisation, and as such regular monitoring of herbage mass (HM) provides essential information to assist on-farm decision making. Unfortunately, this practice is seldom carried out on commercial farms, likely due to the time commitment required across the entire grass growing season. Recent studies have shown, however, that even moderately inaccurate HM data can improve the system-side profitability compared to enterprises with no data, warranting further investigations into the trade-off between the accuracy and cost associated with HM measurements. Using a weekly multi-paddock dataset from the North Wyke Farm Platform (NWFP) in Devon, UK, this study evaluated the technical validity and labour-saving potential of a simplified 'pasture walk' protocol for rising plate meters, under which only data along the diagonal transect — rather than the industry-standard W-shaped pathways — of the paddock are collected. Across 234 temporal-paddock combinations, the mean absolute difference in HM estimates derived under the two methods was 106 kgDM/ha, a scale far too small to alter sward or animal management. Spatial simulations with 192,000 iterations supported the generality of this finding beyond the HM distributions actually observed at the study site. With a 51.2% reduction in labour time across paddocks of various sizes and shapes, the proposed method may facilitate the uptake of evidence-based grazing management amongst farmers who currently do not quantify HM at all.

## 3.1. Introduction

Economic and environmental performances of pasture-based livestock enterprises are strongly associated with the efficiency of their grazing systems (Borges et al., 2014). This efficiency is primarily determined by the internal level of pasture utilisation, generally more so than decisions on external inputs newly introduced into the system (Taube et al., 2014; Hyland et al., 2018). Greater pasture utilisation, in turn, is achieved through accurate and timely grazing management (McSweeney et al., 2019), where near real-time information on HM is essential for estimating the amount of forage available both then and in the future ('t Mannetje, 2000).

The most accurate method to quantify the current HM is the physical clipping of forage within quadrats randomly placed across pastures. However, the small size of an individual quadrat necessitates a large number of replicates to produce a value representative of the entire management unit, and as such the labour requirement for this exercise is seldom commercially viable (Martin et al., 2005). Consequently, the vast majority of farmers resort to non-destructive alternatives, with visual assessment ('eyeball method') being by far the most popular approach. Unfortunately, the resultant estimates are known to frequently suffer from low accuracy and low repeatability, especially in the absence of a conscious and continuous effort for calibration (Stockdale, 1984; Piggot, 1986; O'Donovan et al., 2002).

To achieve an optimal balance between the cost (initial outlay and labour requirement) and return (accuracy) of HM measurements, various rudimentary tools such as Robel poles, capacitance meters and sward sticks have been developed to date. Of these, rising plate meters (RPMs) are often considered to be one of the most theoretically attractive options (Gourley and McGowan, 1991). Invented in the late 1970s (Castle, 1976), a typical RPM features a circular plate of a known diameter, through which a vertical shaft freely passes. As the shaft is lowered to the ground, the compressed sward beneath causes the plate to rise along the shaft, and the vertical distance of this plate movement (compressed sward height: CSH) is recorded for each landing event (McSweeney et al., 2019). The measurement is subsequently converted to an HM value using an equation pre-calibrated for the relevant species composition and growth stage of the sward. HM estimates derived from an RPM are generally within 5-10% of the true value (Sanderson et al., 2001; Murphy et al., 2020b) and, owing to the light weight and the long shaft that can be held above the waist level, its use requires little more physical activity than a simple walk across the pasture.

Yet, despite the seemingly apparent benefit of its use for grazing management, the global adoption rate of RPM remains low (DEFRA, 2020b; McConnell et al., 2020). While the exact mechanism behind this tendency has not been completely elucidated, the regular time commitment required for ‘pasture walks’ is plausibly thought to be a primary deterrence (Romera et al., 2010, 2013). In particular, most RPM manufacturers and extension specialists who support its use recommend that readings are taken in a circuitous path across each paddock to account for spatial variability of HM distribution (Thomson, 1983; Sanderson et al., 2001; DairyNZ, 2008; MacAdam and Hunt, 2015; ADAS, 2016; Manjunatha and Rocateli, 2018). Nevertheless, studies elsewhere have suggested the law of diminishing returns, with an increase in measurement effort not guaranteeing a proportional increase in precision (O’ Sullivan et al., 1987; Hutchinson et al., 2016). When this is indeed the case, extra walks could result in a suboptimal allocation of on-farm labour time and, equally importantly, the prospect of long walks could psychologically dissuade farmers from regularly measuring HM (Murphy et al., 2020a).

The objective of the present study, therefore, is to evaluate the technical validity and time-saving potential of an alternative RPM sampling technique that requires less labour input. Specifically, HM estimates from pasture walks of the shortest distance — diagonally linking two corners of the paddock — are compared against those from conventional walks along W-shaped transects, with the view to identify conditions under which 'shortcutting' is permissible without a large loss in accuracy. Following an analysis of a primary dataset that encapsulates the seasonal variability in spatial structure of swards, spatial simulations are also carried out to evaluate the generality of the findings beyond the HM distributions observed at the study site.

## 3.2. Materials and methods

### 3.2.1. Study site and farming system

The study site and associated farming system are described in depth within Chapter 2; the following paragraph contains information pertinent to this particular study.

Data for the present study were collected from the non-reseeded farmlet ('Green') to allow the widest possible applicability of findings to commercial farms in the UK **(Figure 3.1)**. This farmlet is in turn split into seven paddocks, none of which had been reseeded for at least 30 years prior to the commencement of this study **(Table 3.1)**. Species composition was largely homogenous across the entire farmlet, dominated (>60%) by perennial ryegrass (*Lolium perenne*) but with creeping bent (*Agrostis stolonifera*), Yorkshire fog (*Holcus lanatus*) and marsh foxtail (*Alopecurus geniculatus*) also contributing a smaller biomass (Takahashi et al., 2018).

### 3.2.2. Data collection and non-spatial analysis

Forage data for this study were collected over a seven-month period of March–October 2019, covering the entire grass growing period at the study site **(Table 3.2)**. CSH was measured weekly using a Jenquip EC20 Bluetooth Electronic Platemeter (NZ Agriworks Ltd, Feilding, New Zealand) and subsequently converted to HM using a calibration equation of $HM = CSH\ (cm) \times 140 + 500$, which has been calibrated for comparable climate and sward type (Klootwijk et al., 2019). As this equation represents a linear relationship between CSH and HM, the results of statistical tests reported below (including *p*-values) are neutral from the selection of the slope and intercept. Following the manufacturer's recommended protocol (Sanderson et al., 2001), approximately 30 RPM readings per paddock were taken under each sampling, with precalculated pacing (number of footsteps) used to estimate recording intervals. The readings were then exported to the *Agrinet* (https://www.agrinet.ie) cloud-based farm management software via the *Pastureprobe* (https://www.pasturemeters.co.uk/ pasture-app) smartphone app for data storage.

The sampling was repeated twice on each day on each paddock, with a straight-line diagonal transect (treatment: **Figure 3.2a**) and the manufacture-recommended W-shaped transect (control: **Figure 3.2b**) walked successively using the same equipment and operator. Recording intervals were longer under W-transects due to the longer travel distance. The final dataset thus compiled contained 34 weekly sampling events across seven paddocks, yielding a total of 234 date-paddock combinations. Four observations in September were missing due to application of farm-yard manure (FYM) immediately before the designated sampling dates on the relevant paddocks. GPS coordinates of individual RPM readings were also recorded for the latter 28 weeks of the sampling period, or 192 date-paddock combinations (28 x 7 minus 4 missing values: **Table 3.2**).

The average HM under each date-paddock combination was estimated separately for diagonal- and W-transects. The HM difference between these sampling methods was then evaluated in two formats, as the absolute difference (to identify the scale of discrepancy) and as the relative difference (to identify the tendency of overestimation or underestimation), for each date-paddock combination while taking the W-transect value as the ground truth. Furthermore, to investigate factors affecting these discrepancies, linear regression models were estimated for both absolute and relative differences using paddock-specific and time-specific covariates summarised in **Table 3.3**. In order to account for the potential effect of unobservable paddock-specific variables, fixed effect specifications were also tested for both absolute and relative differences.

### 3.2.3. Spatial analysis

While the NWFP replicates land use and farm management strategies commonly adopted across temperate grassland regions, HM data observed therein are necessarily influenced by weather and paddock allocation (fence lines) intrinsic to the study site. Furthermore, the soil, topography, and seasonal livestock usage unique to each paddock are likely to affect the spatial dependence (autocorrelation) in HM on that particular paddock. In order to partially overcome this limitation and appraise the generality of the findings obtained from the above analysis, conditional geostatistical simulations (Journel, 1996) were conducted with the 28-week subset of the HM data for which GPS information was available.

As a preliminary analysis, Moran's *I* (Moran, 1950), an index for spatial autocorrelation of a variable, was initially obtained for HM for each date-paddock combination. The value was calculated under an inverse distance weighting function and enabled a simple test of significance for spatial autocorrelation. Following this exercise, a more detailed structure of spatial autocorrelation in HM under each date-paddock combination was evaluated using Cressie's robust sample variogram estimator (Cressie and Hawkins, 1980), which is suitable for a small sample size with influential outliers. For each sample variogram, an exponential variogram model was then fitted using a weighted least squares method (Zhang et al., 1995). The latter (model) variogram provides a smooth representation of the former (sample) variogram and is characterised by three parameters, the nugget, sill variances and correlation range. Each of these model variograms represents the spatial structure of HM across the entire paddock on a given date, summarising the patterns of autocorrelation attributable to latent factors.

The parameters from each variogram model were subsequently used to produce 1000 realisations of the spatial HM distribution (192,000 realisations across all date-paddock combinations), with simulations conditioned by the HM values (and coordinates) observed under actual W-transect sampling. Conceptually, each realisation corresponds to a HM pattern that was as likely to have materialised as the pattern actually observed **(Supplementary Figure 3.S1)**. Finally, the HM values at the actual sampling locations along the diagonal-transect were extracted for each realisation, with the aim of evaluating whether the selection of sampling method systematically affects the resultant HM estimates.

Both Moran's *I* and sample variograms were derived using a combined dataset of HM values from both diagonal- and W-transects. It is conceded that, ideally, only the W-transect data should be used for these purposes, as the diagonal-transect data can be seen as a probabilistic realisation of the underlying (and therefore unobservable) spatial model. Notwithstanding, strong evidence exists that a measure of spatial autocorrelation is more likely to be compromised if estimated from a small sample unevenly located across the area of interest

(Webster and Oliver, 2008; Webster and Lark, 2012) and, as such, the pragmatic decision was taken to facilitate clearer characterisation of spatial structure in HM for each date-paddock combination. For spatial simulations, this decision only concerns their parameterisation (via the three variogram parameters) and not the data used to condition them.

#### 3.2.4. Statistical software

All data analysis was conducted using R version 3.6.3 (R Core Team, 2020). The 'gstat' package (Pebesma, 2004) was additionally deployed for spatial simulations.

## 3.3. Results

### 3.3.1. Pasture growth during the study period

The weather observed during the study period largely followed a typical annual cycle at the study site, characterised by a high temperature/solar radiation and a low rainfall in mid-summer, and the opposite in the spring and autumn **(Figure 3.3a)**. A notable exception was a week in mid-June with a high level of rainfall and a period in early July that saw an extremely low level of rainfall alongside a high level of solar radiation (and thus evaporation), likely contributing to the generally low HM throughout the month of July **(Figures 3.3b-3.3h)**.

Pasture cover ranged between 1350-5500 kgDM/ha during the study period. Following the typical pattern of a UK grazing season, pasture growth peaked at mid-spring **(Figures 3.3d & 3.3g)** and then gradually declined throughout the year until late autumn. Despite regular application of inorganic nitrogen and FYM, pasture cover remained relatively constant on grazed paddocks as a consequence of the continuous variable stocking strategy. Paddocks primarily used for grazing sheep **(Figures 3.3b & 3.3c)** had a lower HM than those used for grazing cattle **(Figures 3.3f & 3.3g)** due to target sward heights to accommodate the distinct grazing behaviours of the two species. Based on the graphical representation of weekly pasture cover, there appeared little difference in HM estimates between the diagonal- and W-transect sampling patterns throughout the grazing season **(Figures 3.3b-3.3h)**.

### 3.3.2. Effect of sampling method — analysis of raw data

Across all dates and paddocks, the mean differences in HM recorded under diagonal- and W-transects were 106 kgDM/ha (absolute difference) and 11 kgDM/ha (relative difference), respectively **(Figure 3.4)**. The frequency distribution of the relative difference across 234 date-paddock combinations suggested that the direction of discrepancy is largely balanced, with 5% and 95% quantiles of -244.7 kgDM/ha and 252.0 kgDM/ha, respectively. This distribution however was non-normal ($p$ < 0.001 based on Shapiro-Wilk test) due to shallow and long tails on both sides.

A paddock-by-paddock analysis revealed a small but systematic overestimation under diagonal-transects on a single paddock (paddock 7, **Supplementary Figure 3.S2**). When the relative difference data from all paddocks were split into three groups of an equal size based on the absolute level of HM, the distributions for high cover (> 2694 kgDM/ha) and medium cover (2215-2694 kgDM/ha) groups were not statistically different from being normal ($p$ = 0.226 and 0.473, respectively). The low cover group (< 2215 kgDM/ha), however, demonstrated a mild skewness to the left ($p$ < 0.001), with 5% and 95% quantiles of -86 kg and 171 kg, respectively **(Supplementary Figure 3.S3)**. Causes and implications of these findings will be discussed in the next section.

The results of linear regressions were consistent with the above findings, with a lower pasture cover associated with a slight overestimation from diagonal-transect sampling **(Table 3.4)**. As previously identified, diagonal-transect readings at paddock 7 were shown to be overestimated by ~110 kgDM/ha on average. Stocking densities also showed a weak effect on the relative difference, with an additional 1 LU/ha linked to a 24-33 kg/ha of overestimation. All in all, however, relatively little effect was detected from either paddock-specific or time-specific covariates regardless of the model specification selected.

### 3.3.3. Effect of sampling method — spatial analysis

Across 192 unique date-paddock combinations Moran's *I* values from 134 observations (70%) were statistically significant ($p < 0.05$), indicating that HM distributions are often spatially autocorrelated. This autocorrelation was predominantly in the form of a weak positive correlation, under which RPM readings from neighbouring sampling points were more likely to show similar values **(Figure 3.5)**. When the absolute difference in HM between sampling methods was split into two groups according to the significance of associated Moran's *I* values, the average amongst the autocorrelated group (119 kgDM/ha; $n$ = 134) was smaller than that amongst the uncorrelated group (93 kgDM/ha; $n$ = 58). This 'difference in differences' was also statistically significant based on the independent sample *t*-test, although a 26 kgDM/ha difference is likely to be too small to have a practically meaningful impact on grazing management decisions.

Across 192,000 iterations of simulated HM spatial patterns along the diagonal-transects, the mean relative difference between sampling methods (simulated HM along the diagonal-transect minus 'true' HM along the W-transect) was 10 kgDM/ha, with the 90% range of -181 to 212 kgDM/ha **(Figure 3.6)**. When this distribution was further broken down into separate paddocks, slightly more variations were evident amongst larger paddocks **(Supplementary Figure 3.S4)**. Nonetheless, the interquartile range was never greater than 200 kgDM/ha, with the largest 90% range of -285 to 300 kgDM/ha (paddock 6).

## 3.4. Discussion

### 3.4.1. Viability of the diagonal sampling method

The mean absolute difference in HM between sampling methods was 106 kgDM/ha across all date-paddock combinations, with greater discrepancies observed when pasture cover was lower and measured on a particular paddock (paddock 7). The generally high level of agreement between the two methods was also supported by spatial simulations, which accounted for the probabilistic nature of the observed (spatial) HM distributions in the real world.

Inaccurate estimation of HM necessarily results in poor allocation of forage resources both amongst animals and across time (McSweeney et al., 2019). While small errors arising from miscalibration is likely to be harmless for practical purposes (Rayburn and Rayburn, 1998), it has been suggested that for the labour cost to be justified, the error in yield estimation must be lower than 10% (Sanderson et al., 2001). Within the present study, the average discrepancy in yield estimation between sampling methods was 4.0%, with 91.6% of date-paddock combinations recording a discrepancy of 10% or below. Although these values are solely based on the difference attributable to walking patterns (implicitly assuming that measures on W-transects are 100% accurate) and therefore do not account for measurement errors inherent to the RPM technique and independent of the sampling strategy, information gained from diagonal-transect sampling was, at minimum, largely comparable to that gained from W-transect sampling.

### 3.4.2. Impact of sampling methods on technology uptake

Improvements in labour efficiency is one of the foremost reasons that influence the uptake of precision agriculture technologies (Olaizola et al., 2008; Barnes et al., 2019b; a). In the current study, GPS timestamps provided a reasonably accurate estimate on the time saved by walking a diagonal-transect rather than a W-transect. On average, the diagonal walk resulted in a 51.2% reduction in time, requiring 1.2 min/ha rather than 2.5 min/ha across seven paddocks of different sizes and shapes. If a 100 ha grazing platform is sampled weekly with a paid labour cost of £10/hr, this would result in an estimated annual saving of £1,128.

More importantly, the reduced labour requirement is likely to facilitate the uptake of the technology amongst farmers who do not currently estimate HM in any formal way (Murphy et al., 2020b). Even in the improbable event that diagonal-transect sampling reduces the estimation accuracy, imperfect information on HM often results in a substantially greater resource use efficiency when compared to no information at all. For example, a recent study demonstrated that the possession of HM estimates with an average measurement error of 15% would increase the farm profitability by £197/ha (Beukes et al., 2019). Elsewhere, studies have also established a strong causal link between the measurement of pasture cover and dry matter production and pasture utilisation (García and Holmes, 2005; Kennedy et al., 2006; Creighton et al., 2011; Mccarthy et al., 2013; Hanrahan et al., 2017; Murphy et al., 2020a) and, separately, between pasture utilisation and farm profit per hectare (Dillon, 2011; Mayne and Bailey, 2016).

### 3.4.3. Limitations of the diagonal sampling method

As discussed, RPM readings from diagonal-transects on paddock 7 consistently overestimated HM by ~110kgDM/ha and the reason for this tendency remained unidentified following regression analysis. However, a closer look at the field shape revealed that a large proportion of the 'natural' W-transect on this particular paddock is drawn parallel to a fence line, in a region where pasture cover is generally lower due to livestock congregating at the field boundary **(Supplementary Figure 3.S5)**. The observed 'overestimation' in this particular instance, therefore, is likely to be a consequence of an underestimated HM under the W-transect, providing a further case for the labour-saving alternative. Notwithstanding, care should be taken before extending the current result to a general recommendation across temperate grasslands, as the spatial structure that governs the HM distribution is influenced by many, and oftentimes unobservable, factors.

For example, microclimates created by landscape and spatially diverse morphological characteristics of the soil can both lead to substantial variation in pasture species composition and thus HM distribution within a single paddock (Harmoney et al., 1997). Furthermore, grazing livestock's tendency to avoid long, stemmy herbage can create a mixture of short and tall patches within grass swards (Barthram et al., 2005), especially towards the latter part of the season (Hirata, 2000). At a high stocking density, this selective grazing can also be exacerbated by excreta, as animals tend to reject areas contaminated by dung and urine (Klootwijk et al., 2019). Multi-species swards, of which health and nutritional benefits are increasingly recognised (Roca-Fernández et al., 2016), also makes HM estimation notoriously challenging, as their species composition not only varies within a paddock but also by the season (Martin et al., 2005). When any of these factors is likely to be a dominant determinant of spatial HM distribution, the benefit of the greater spatial capture provided by W-transects may outweigh their labour cost. Discussions above also highlight how the spatial orientation of the transects can affect HM estimation when the chosen path does not traverse all key sources of HM variation. Future work combining multiple farm data and further spatial simulations could investigate this issue in more detail.

While the present study was undertaken at a lowland grassland, cattle and sheep are also grazed in marginal and upland areas (FAO, 2011) where physically measuring HM is practically challenging, excessively time consuming and ultimately inaccurate (Ledgard et al., 1982; Hutchinson et al., 2016). It is acknowledged that a mere reduction in labour requirement is unlikely to make the RPM an attractive farm management tool in these environments. However, alternative technologies such as those discussed below may provide a potential solution.

### 3.4.4. Alternative methods and technologies

Advancements in technology have driven the emergence of new techniques which could eventually replace the RPM as a means of measuring HM. Remote sensing can provide timely and accurate data for informing management decisions in a semi-automated fashion (Atzberger, 2013) and is of particularly high economic value when large areas are studied (Reinermann et al., 2020). Poor spatial resolution limits its use for accurate monitoring of forage utilisation short-term although this issue is progressively being addressed in the industry (Booth and Cox, 2011; Gillan et al., 2019).

Alternatively, the use of unmanned aerial vehicles (UAVs or 'drones') has also increased in popularity over recent years (Alvarez-Hess et al., 2021; Théau et al., 2021). UAVs provide a number of advantages over satellites (and piloted aircrafts), as they are relatively low-cost and safe, can be deployed quickly and repeatedly and can provide imagery at a higher resolution (Rango et al., 2009). UAVs also provide some advantages over on-field approaches, as they are less time consuming (Michez et al., 2019) and, once initial data training is complete, often provide more accurate results than the RPM (Michez et al., 2020). However, due to the requirements of stable weather and environmental conditions (Von Bueren et al., 2015), high initial costs (Poley and McDermid, 2020), strict aviation regulations and unintuitive calibration processes, interest from farmers in this technology has been surprisingly underwhelming (Zhang and Kovacs, 2012). I am currently investigating the exact cause of this phenomenon, and in particular whether it is more economic or psychological; regardless, rudimentary approaches more accessible to farmers are likely to stay as a primary method of HM estimation, at least for the foreseeable future.

Finally, it is worthwhile noting that, theoretically speaking, RPM measurements do not have to follow a pre-determined transect at all. Nakagami (2016), for example, proposed an algorithm to estimate the average HM solely based on two RPM recordings per paddock, from the locations with the highest and lowest covers identified following a full pasture walk. Jordan et al. (2003), on the other hand, proposed an equilateral triangular sampling pattern as the best compromise between interpolation accuracy and sampling efficiency, especially when forage quality (N, P, K and S contents) is also of an interest. These non-transect approaches were outside the scope of the present study, as additional labour requirements associated with them are unlikely to be well-received by a large proportion of livestock farmers in the study region. On farms where no HM data are currently recorded, the simpler and easier approach tested herein is likely to provides the best attainable balance between the cost and benefit of information.

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**Table 3.1.** Description of paddock data for 2019 grazing season

| | Paddock name | | | | | | |
|---|---|---|---|---|---|---|---|
| | Longlands South | Dairy North | Golden Rove | Orchard Dean South | Orchard Dean North | Burrows | Bottom Burrows |
| **Description** | | | | | | | |
| Paddock code | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Area (ha) | 1.7 | 1.8 | 3.9 | 3.9 | 2.5 | 6.4 | 1.3 |
| Elevation (m) | 161.88 | 160.04 | 172.26 | 160.02 | 160.02 | 157.91 | 143.53 |
| Average slope (deg) | 4.17 | 6.23 | 5.65 | 6.99 | 6.99 | 6.92 | 3.49 |
| **Usage** | | | | | | | |
| Sheep | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Cattle | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Silage | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Soil Parameters*** | | | | | | | |
| Total C (%w/w) | 4.65 | 5.93 | 5.78 | 6.1 | 6.35 | 5.78 | 5.36 |
| Total N (%w/w) | 0.48 | 0.63 | 0.58 | 0.6 | 0.64 | 0.51 | 0.57 |
| Total P (mg/kg) | 1475 | 1633 | 1547 | 1482 | 1552 | 1383 | 1425 |
| **Average stocking rate (LU/ha)** | | | | | | | |
| Sheep | 1.16 | 1.78 | 0.49 | 0.09 | 0.1 | 0.03 | 0.8 |
| Cattle | 0 | 0 | 0.15 | 0.64 | 0.25 | 0.89 | 0.3 |
| Combined | 1.16 | 1.78 | 0.64 | 0.73 | 0.35 | 0.92 | 1.1 |
| **Silaged area (ha)** | | | | | | | |
| First cut | 0 | 0 | 3.77 | 3.84 | 2.47 | 0 | 0 |
| Second cut | 0 | 0 | 1.93 | 0 | 0 | 6.4 | 1.3 |
| Season total | 0 | 0 | 5.7 | 3.84 | 2.47 | 6.4 | 1.3 |

* Values are an average of four samples per paddock, taken at three-monthly intervals during 2019

**Table 3.2.** Paddocks and dates used for analysis shown with seasonal pasture cover

| Paddock name | March | | | | April | | | | May | | | | | June | | | | July | | | | August | | | | | September | | | | October | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) Longlands South | a | a | a | a | a | a | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab |
| (2) Dairy North | a | a | a | a | a | a | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab |
| (3) Golden Rove | a | a | a | a | a | a | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab |
| (4) Orchard Dean South | a | a | a | a | a | a | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | * | | ab | ab | ab | ab |
| (5) Orchard Dean North | a | a | a | a | a | a | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | | | ab | ab | ab | ab |
| (6) Burrows | a | a | a | a | a | a | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab |
| (7) Bottom Burrows | a | a | a | a | a | a | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab | ab |

Low pasture cover — High pasture cover

a - GPS data unavailable, used for results section 1 & 2

b - GPS data available, used for results sections 3 & 4

* Data unavailable due to FYM application

**Table 3.3.** Description of covariates used for linear modelling

| Description | Unit | Time-specific | Paddock specific |
|---|---|---|---|
| Average pasture cover of paddock* | kgDM/ha | ✓ | ✓ |
| Sheep stocking rate[†] | LU/ha | ✓ | ✓ |
| Cattle stocking rate[†] | LU/ha | ✓ | ✓ |
| Nitrogen application[†] | kg/ha | ✓ | ✓ |
| DTM (elevation) | m | | ✓ |
| Slope | ° | | ✓ |
| Soil C | %w/w | | ✓ |
| Soil N | %w/w | | ✓ |
| Soil P | mg/kg | | ✓ |
| Herbage C | %w/w | | ✓ |
| Herbage N | %w/w | | ✓ |
| Precipitation[‡] | mm | ✓ | |
| Air temperature[†] | °C | ✓ | |
| Relative humidity[†] | % | ✓ | |
| Wind speed[†] | km/h | ✓ | |
| Solar radiation[†] | $W/m^2$ | ✓ | |

*according to W-transect sampling

[†]mean of two weeks prior to individual pasture measurement

[‡]total of two weeks prior to individual pasture measurement

**Table 3.4.** Coefficients of regression models investigating differences in pasture cover between techniques

| | Absolute difference | | Relative difference | |
|---|---|---|---|---|
| Covariates | (1)* | (2) | (3) | (4) |
| PaddockCode2[†] | | 15.137 (24.55) | | 59.375 (36.56) |
| PaddockCode3 | | -4.5 (24.88) | | 32.954 (37.06) |
| PaddockCode4 | | 4.473 (26.6) | | 61.828 (39.62) |
| PaddockCode5 | | -4.898 (27.31) | | -14.262 (40.68) |
| PaddockCode6 | | 9.731 (26.66) | | -28.689 (39.7) |
| PaddockCode7 | | 10.726 (23.87) | | 108.337 (35.56) ** |
| Average pasture cover of paddock | 0.062 (0.01) *** | 0.062 (0.01) *** | -0.039 (0.02) * | -0.039 (0.02) * |
| Sheep stocking rate | -0.667 (9.84) | -2.092 (10.09) | -24.479 (14.86) | -32.831 (15.03) * |
| Cattle stocking rate | -7.069 (7.05) | -6.369 (7.14) | -23.985 (10.65) * | -19.881 (10.64) . |
| Precipitation | 0.485 (0.45) | 0.487 (0.45) | -0.03 (0.68) | -0.02 (0.67) |
| Air temperature | 0.189 (2.79) | 0.288 (2.79) | 1.841 (4.21) | 2.42 (4.16) |
| Relative humidity | 2.389 (1.74) | 2.417 (1.74) | 1.028 (2.63) | 1.189 (2.6) |
| Wind speed | -2.507 (3.19) | -2.543 (3.19) | -2.115 (4.81) | -2.325 (4.75) |
| Solar radiation | 0.395 (0.22) . | 0.396 (0.22) . | 0.254 (0.33) | 0.255 (0.33) |
| Nitrogen application | -2.813 (5.44) | -2.293 (5.51) | -0.318 (8.22) | 2.732 (8.2) |
| DTM | -1.313 (1.84) | | 1.31 (2.78) | |
| Soil C | 26.571 (100.38) | | -112.477 (151.6) | |
| Soil P | 0.14 (0.38) | | -0.625 (0.57) | |
| Soil N | -318.157 (914.49) | | 1814.693 (1381.11) | |
| Slope | -1.395 (19.71) | | -4.68 (29.76) | |

Significance codes: *** p < 0.001; ** p < 0.01; * p < 0.05; . P < 0.1

Standard error shown in parentheses

*Four models were tested, two considering paddock-level factors (1 & 3), and two considering paddock itself as a fixed effect (2 &4). Dependent variable was absolute difference (1 & 2) and relative difference (3 & 4) in pasture cover between the two sampling methods.

[†]Paddock code 1 used as the reference factor level

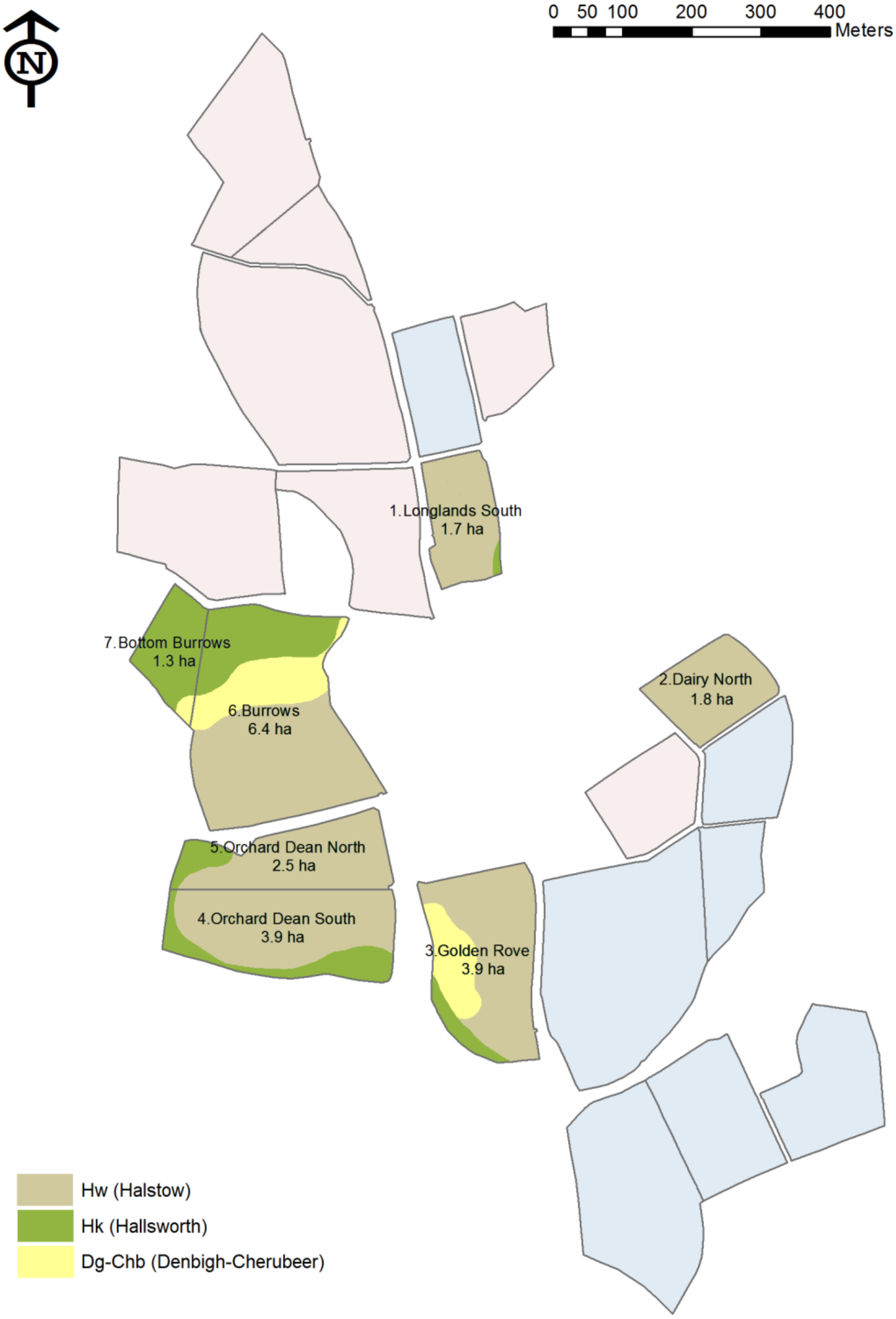



**Figure 3.1.** Soil map of the North Wyke Farm Platform (NWFP). Pasture measurements for this study were taken from labelled paddocks, all of which belong to the permanent pasture treatment.

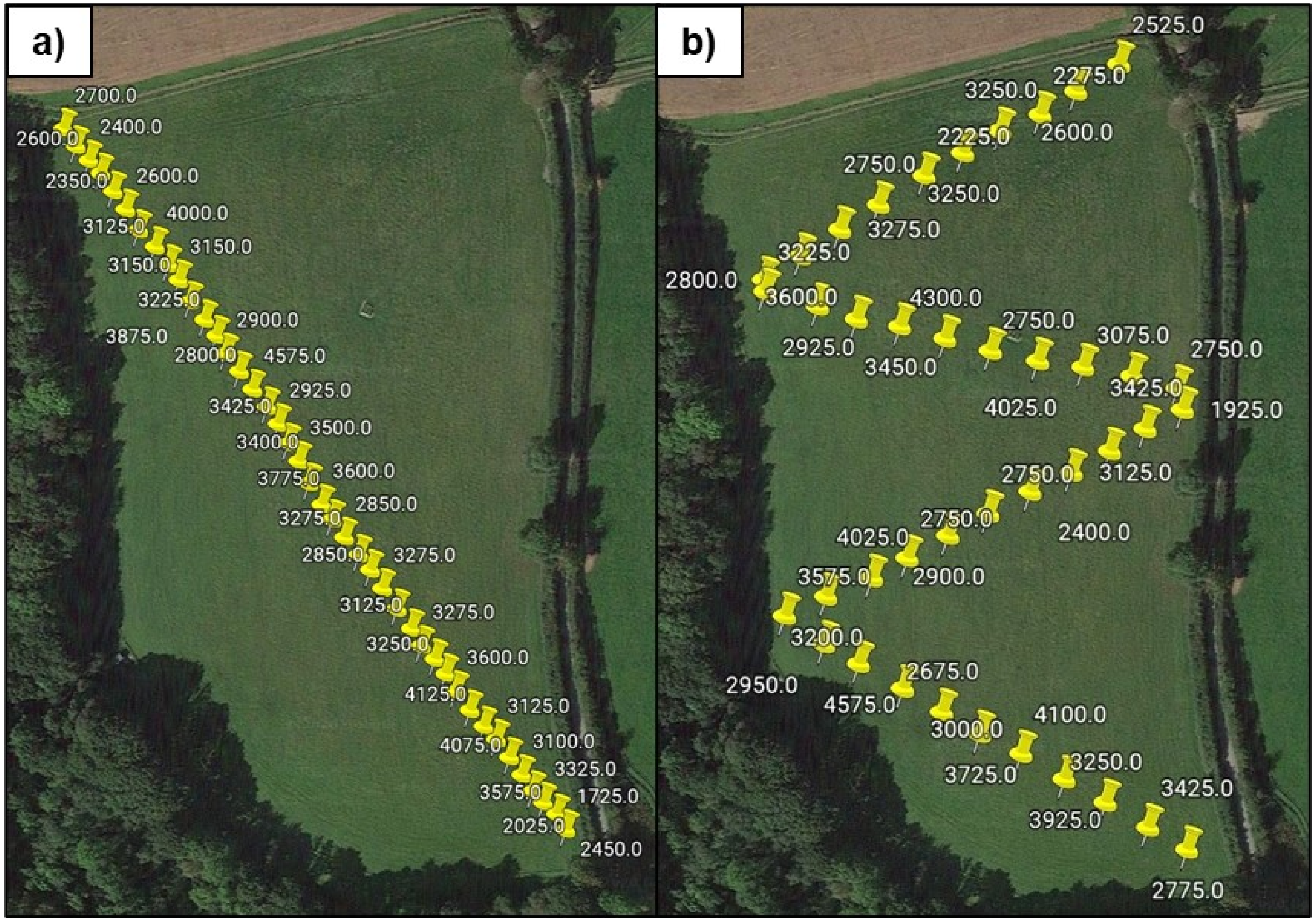
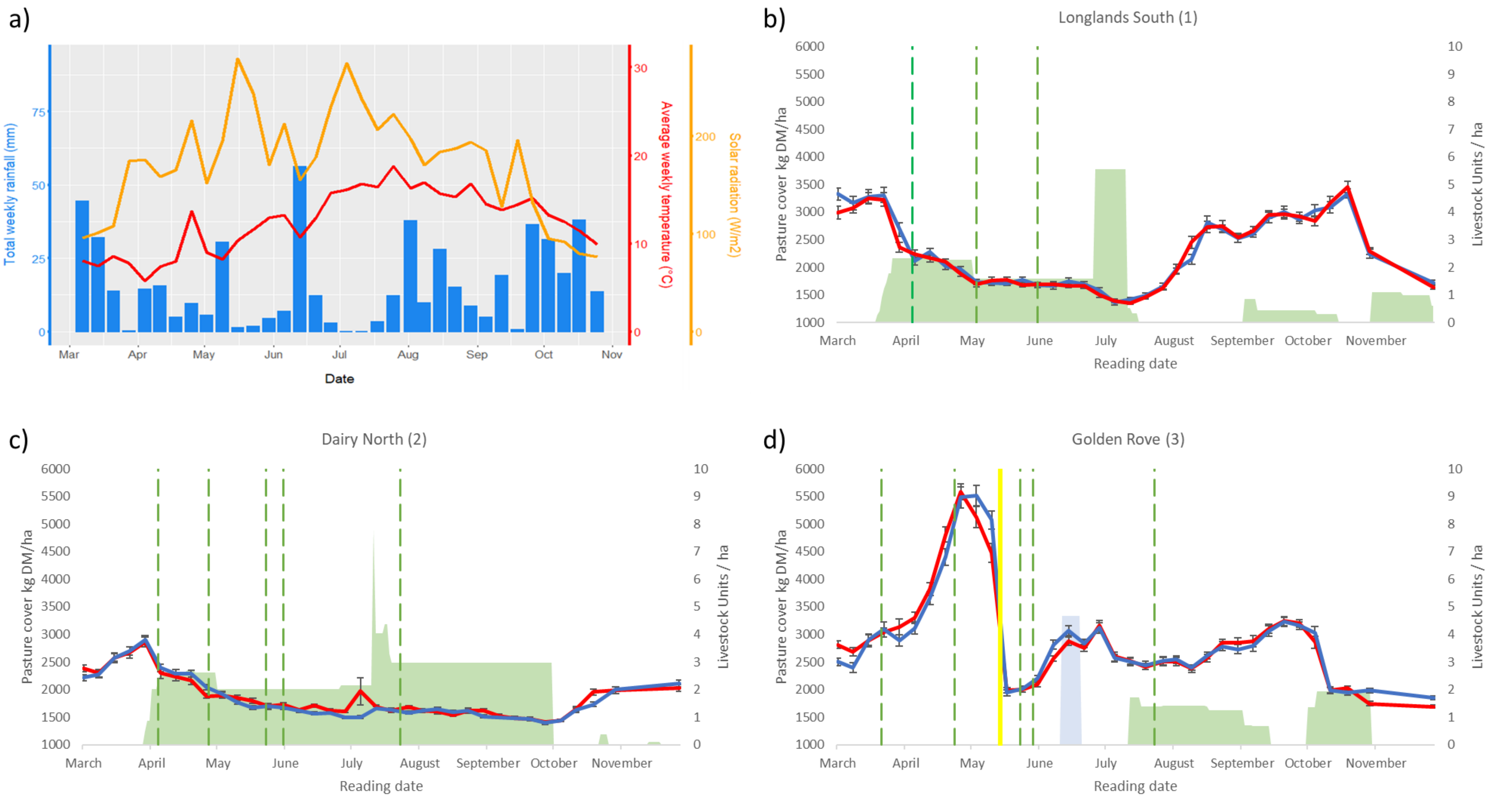



**Figure 3.2.** Schematic example of pasture walk patterns. Weekly pasture readings were taken using diagonal-transect (a) and W-transect (b) sampling methods. Background imagery courtesy of Google Earth.


a)
Total weekly rainfall (mm)
Average weekly temperature (°C)
Solar radiation (W/m2)
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Date
b)
Longlands South (1)
c)
Dairy North (2)
d)
Golden Rove (3)
Pasture cover kg DM/ha
Livestock Units / ha
March
April
May
June
July
August
September
October
November
Reading date

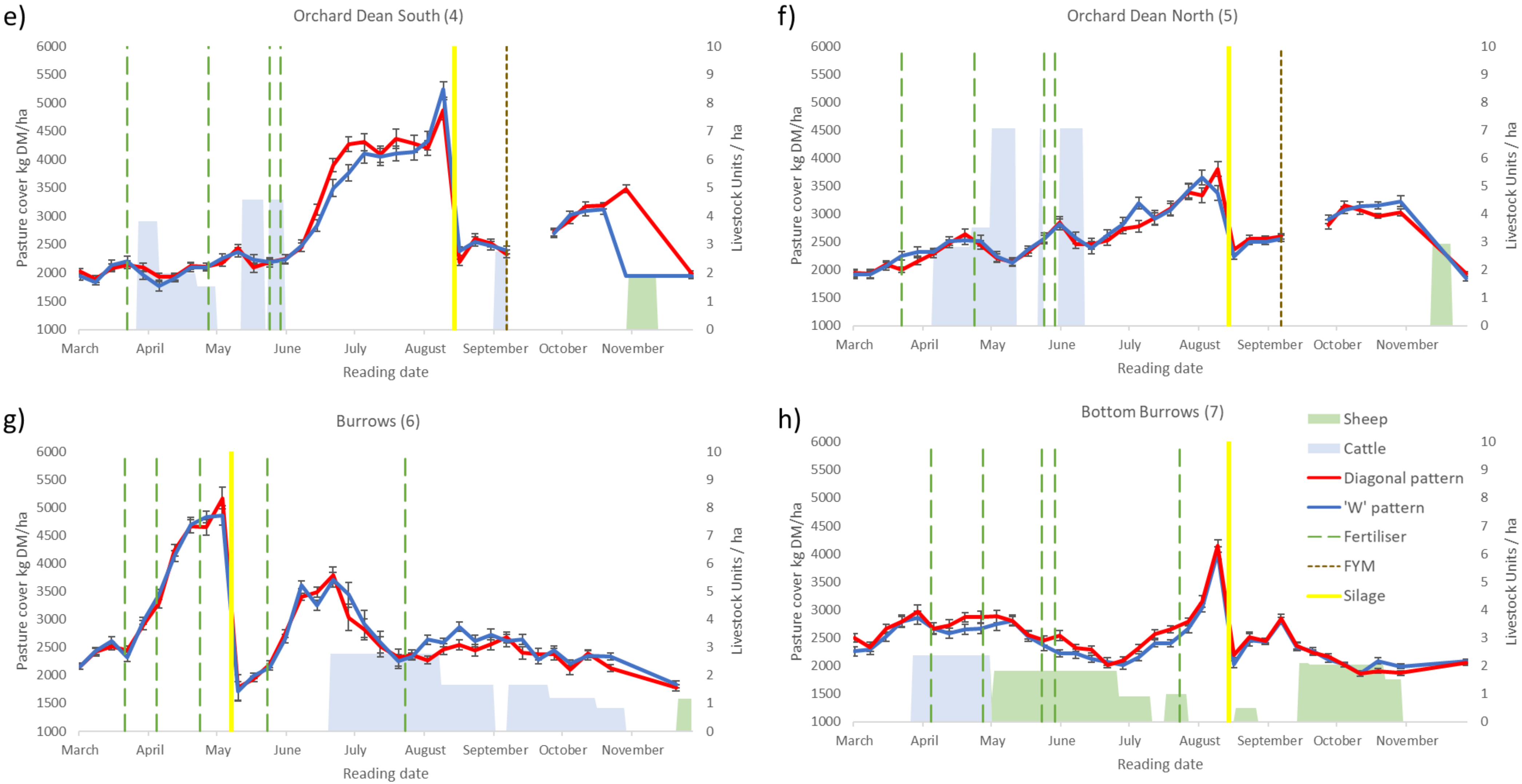



**Figure 3.3.** The impact of field events on changes in pasture cover over the 2019 grazing season, using both diagonal and W pattern sampling methods. Readings not taken for two consecutive weeks following application of FYM (brown dotted line). Panel **A** shows environmental conditions affecting pasture grown throughout the season.

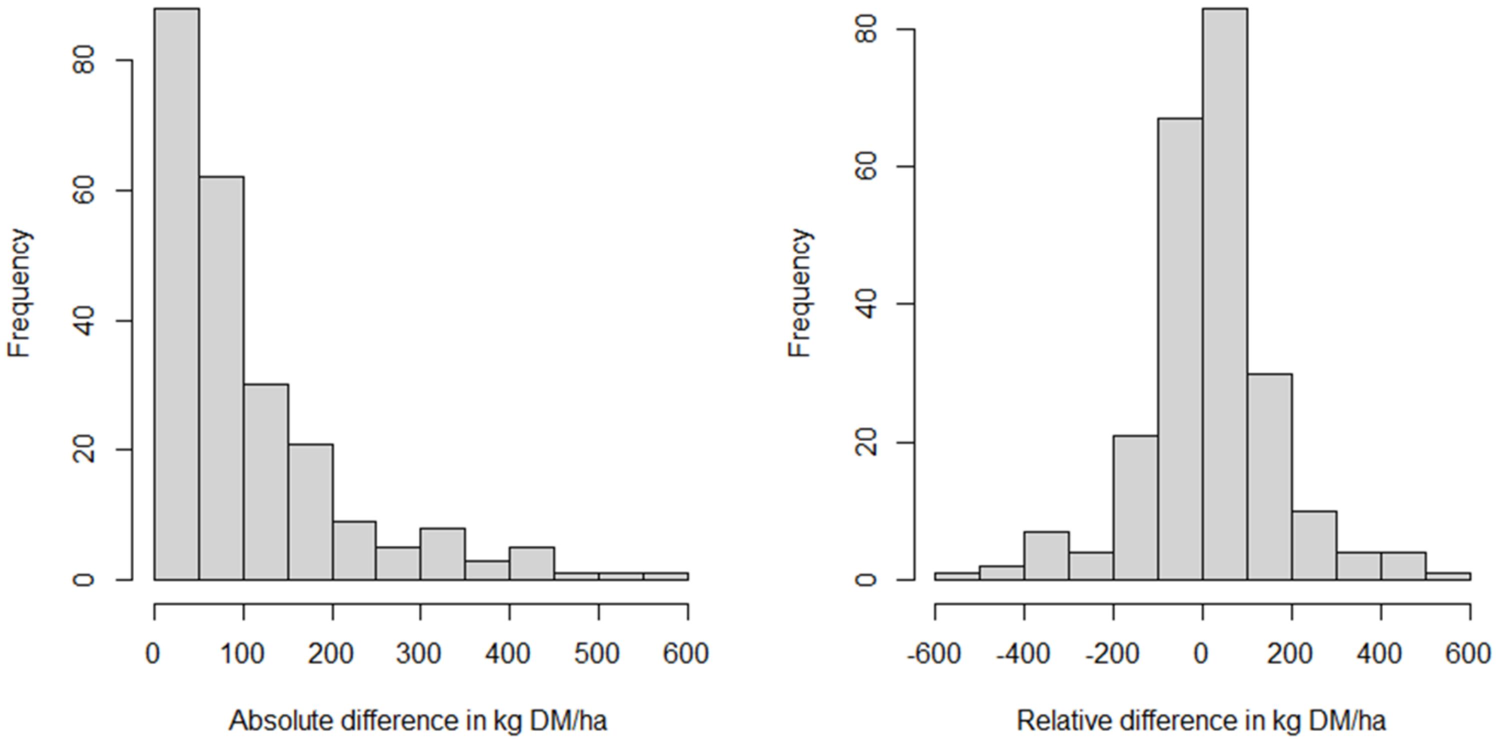



**Figure 3.4.** Histograms for difference between diagonal and W pattern sampling methods across all paddocks and sampling events, measured in kg DM/ha. Relative difference in methods (**right**) calculated by subtracting W pattern readings from diagonal readings, i.e. positive differences indicate diagonal method overestimation.

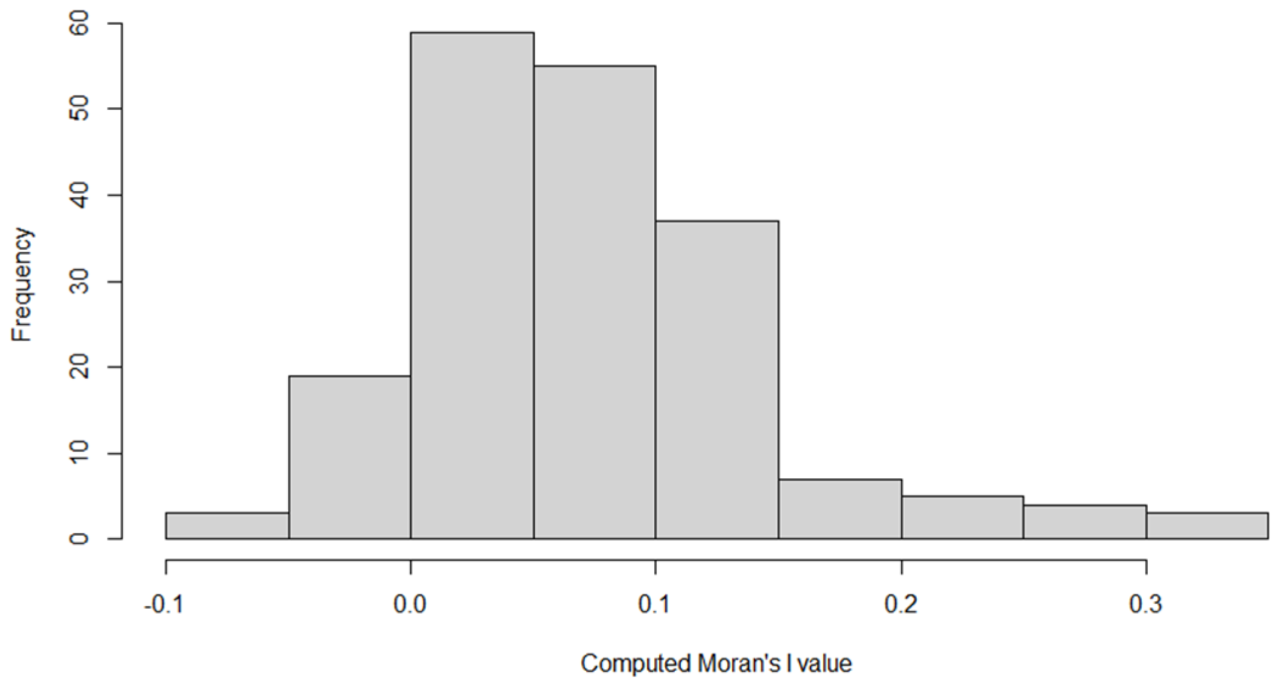



**Figure 3.5.** Histograms of computed Moran's I values for pasture covers measured using W pattern sampling method.

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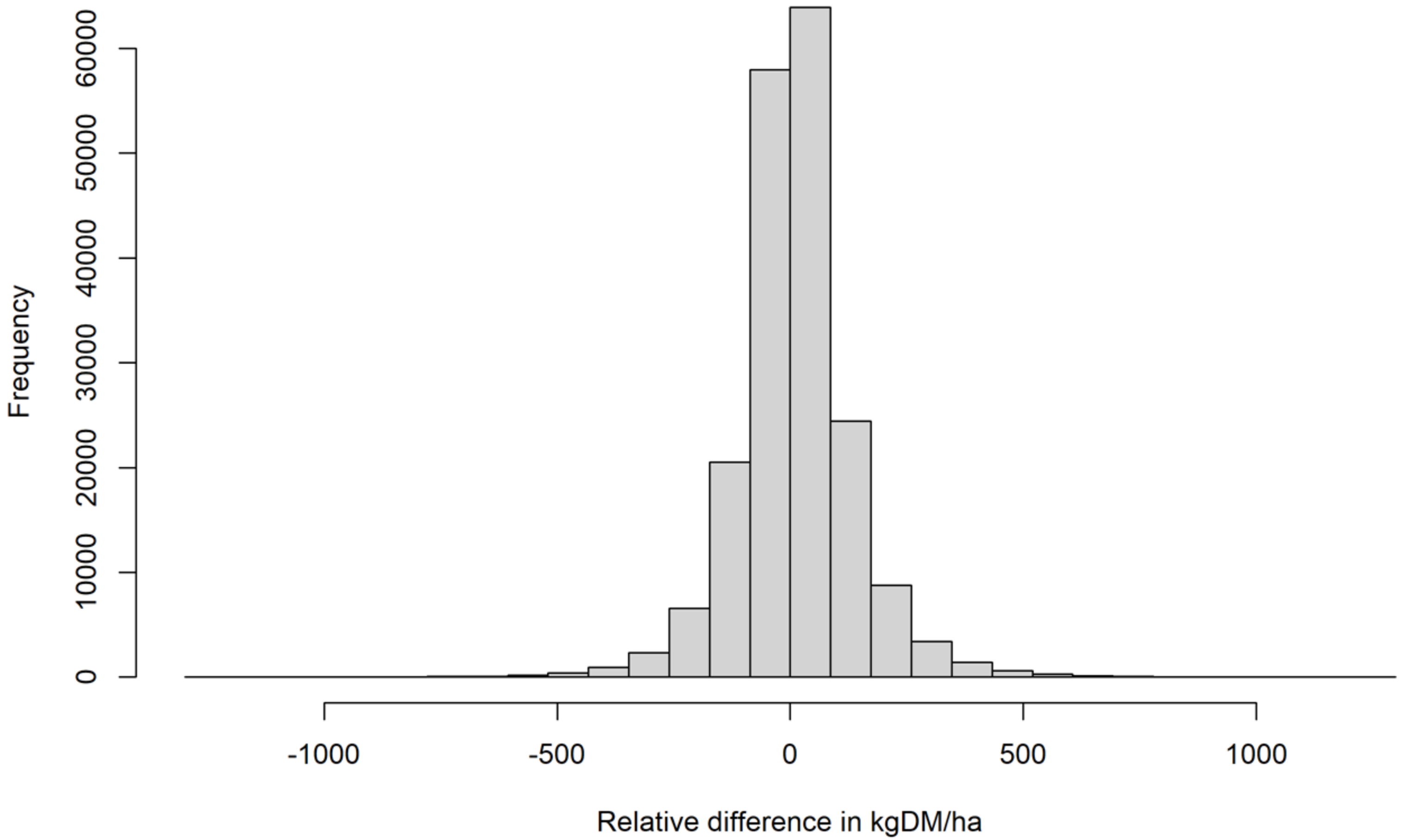


**Figure 3.6.** Histogram of relative difference between simulated HM estimates and actual W-pattern HM estimates. One thousand simulations were computed for each combination of paddock and date code.

## Appendix to Chapter 3.

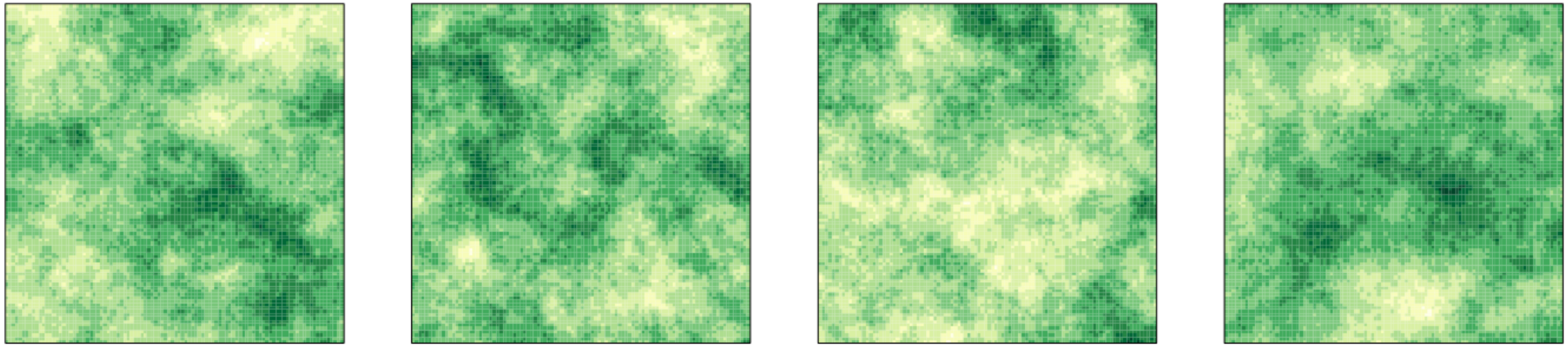

**Figure 3.S1.** An example for four simulated iterations of spatial HM distribution.

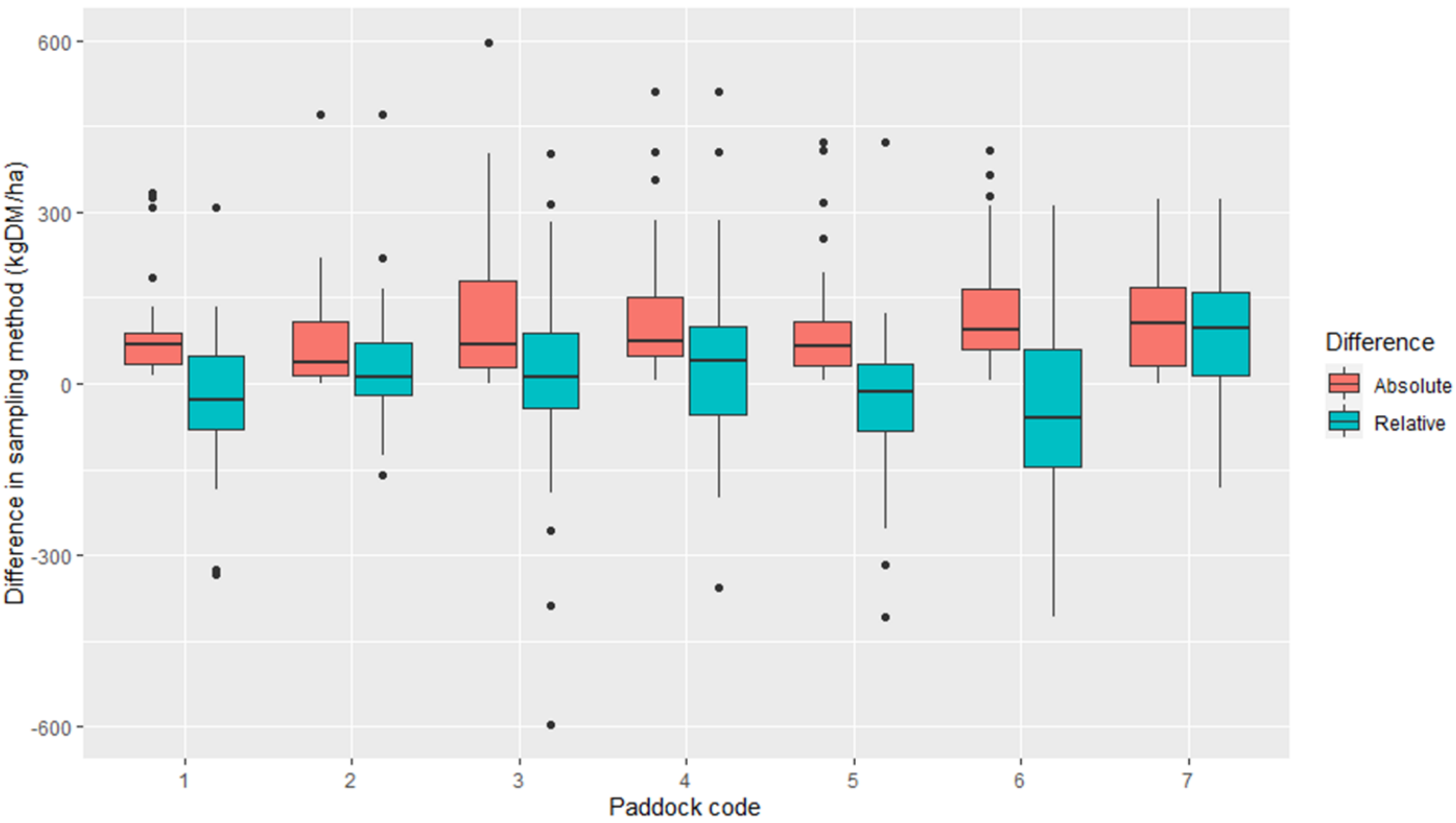


**Figure 3.S2.** Absolute and relative difference in pasture cover estimation between W pattern and diagonal walking patterns, within each paddock. Paddock codes can be cross-referenced in **Table 1** to give paddock names and characteristics**.**

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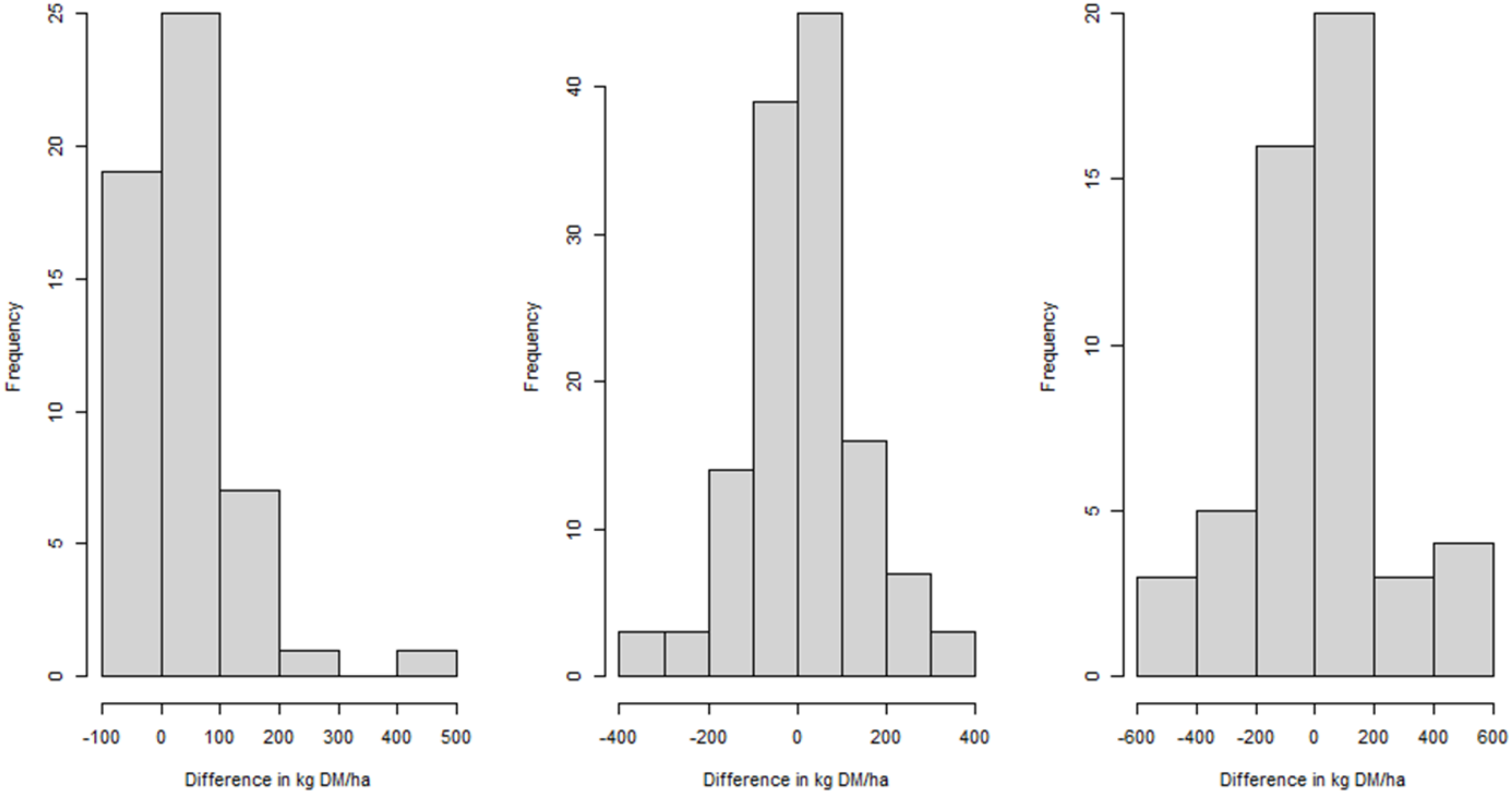


**Figure 3.S3.** Histograms for relative difference between diagonal and W pattern sampling methods across all paddocks and sampling events, measured in kg DM/ha. When divided into three groups based on pasture cover; low, mind and high from left to right, mid and high pasture covers show a normally distributed difference. While low pasture covers are left skewed, suggesting a higher probability of diagonal method overestimating on low pasture covers.

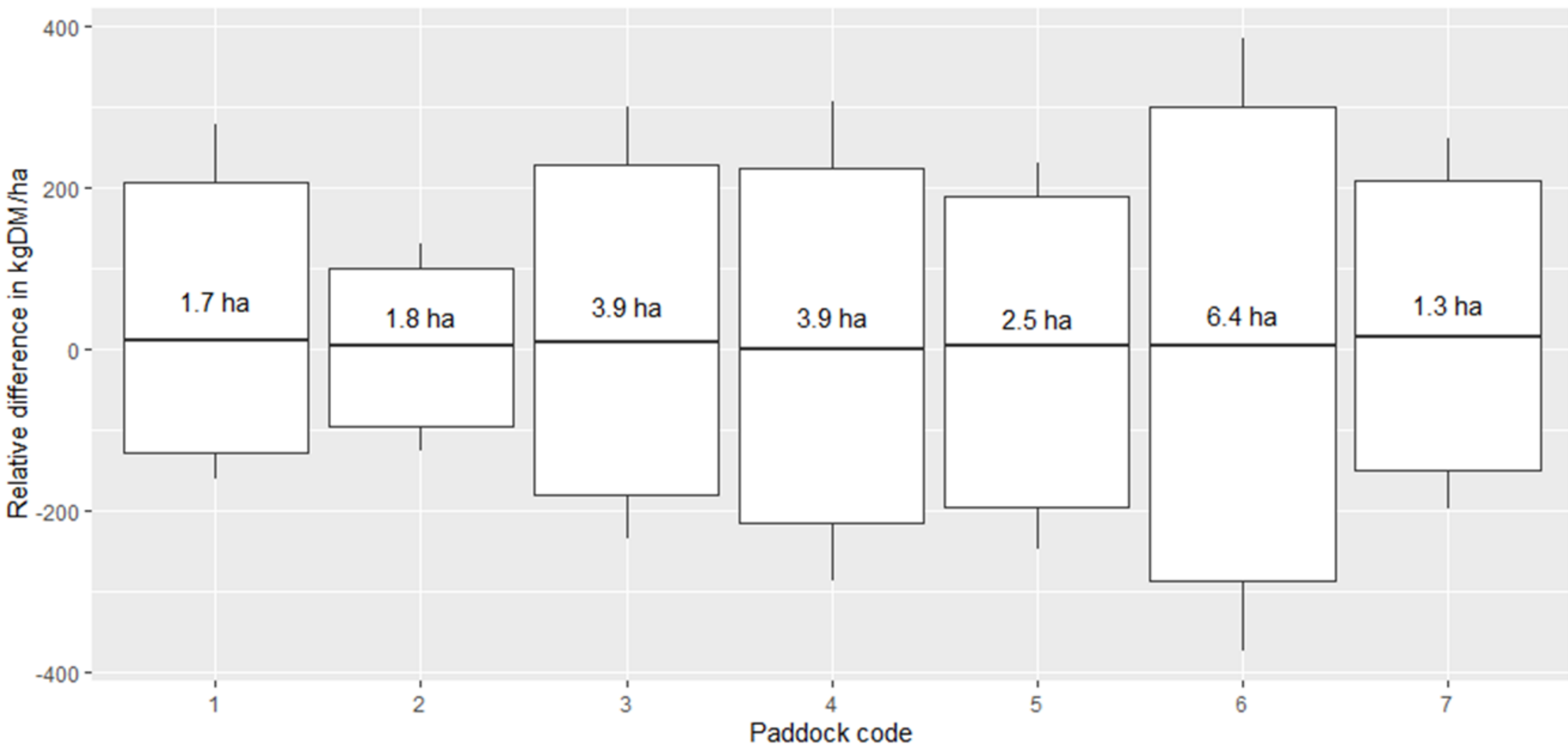


**Figure 3.S4.** Boxplot of relative difference between simulated covers and actual covers using W pattern sampling method, by paddock code. Box area shown with 90% range and whiskers using 95% range. Paddock sizes shown within respective boxes.

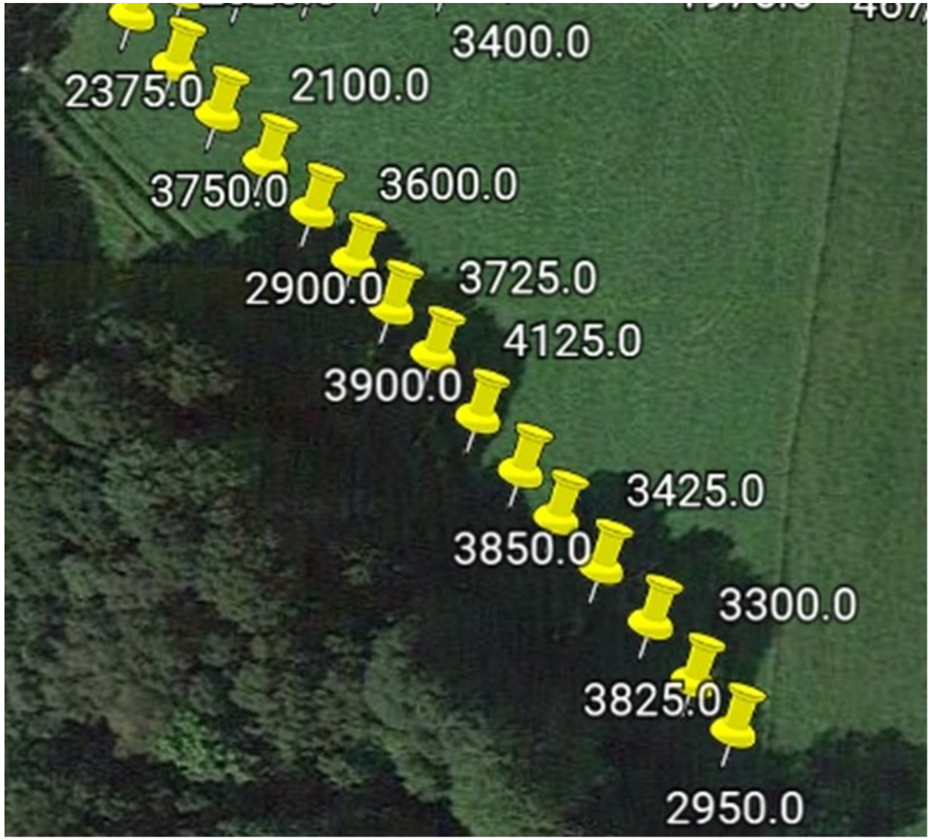


**Figure 3.S5.** Section of W pattern RPM walk running alongside field margin in paddock 7 (Bottom Burrows).

# Chapter 4. Using a lamb's early-life liveweight as a predictor of carcass quality

## Summary

The commercial value of lamb carcasses is primarily determined by their weight and quality, with the latter commonly quantified according to muscle coverage and fat depth. The ability to predict these quality scores early in the season could be of substantial value to sheep producers, as this would enable tailored flock management strategies for different groups of animals. Existing methods of carcass quality prediction, however, require either expensive equipment or information immediately before slaughter, leaving them unsuitable as a decision support tool for small to medium-scale enterprises. Using seven-year high-resolution data from the North Wyke Farm Platform (NWFP), a system-scale grazing trial in Devon, UK, this chapter investigates the feasibility of using a lamb's early-life liveweight to predict the carcass quality realised when the animal reaches the target weight. The results of multinomial regression models showed that lambs which were heavier at weaning, at 13 weeks of age, were significantly more likely to have leaner and more muscular carcasses. An economic analysis confirmed that these animals produced significantly more valuable carcasses at slaughter, even after accounting for seasonal variation in lamb price that often favours early finishers. As the majority of heavier-weaned lambs leave the flock before lighter-weaned lambs, an increase in the average weaning weight could also lead to greater pasture availability for ewes in the latter stage of the current season, and thus an enhanced ewe condition and fertility for the next season. All information combined, therefore, a stronger focus on ewes' nutrition before and during lactation was identified as a key to increase system-wide profitability.

## 4.1. Introduction

The commercial value of lamb carcasses is primarily determined by carcass weight and carcass quality (Rius-Vilarrasa et al., 2009). In meat markets within the European Union, the latter is most commonly represented by premiums and penalties applied according to conformation score (CS) and fat class (FC), which are both visually graded by trained assessors under the EUROP classification system to differentiate products by their genuine economic value (Johansen et al., 2006). Between the two, CS characterises the desirability of carcass shape in terms of convex/concave profiles, which are known to be associated with the proportion of muscle and fat in relation to bone, and thus the quantity of saleable meat. FC, on the other hand, quantifies the amount of subcutaneous fat on the carcass visible to the assessor and is used to select a destination market with the most compatible consumer preference as well as to ensure eating quality, as carcasses which are too lean are more likely to undergo cold-shortening. While the exact scaling system varies from country to country, carcasses in the UK are graded on a 5-point scale (E/U/R/O/P) for CS and on a 7-point scale (1/2/3L/3H/4L/4H/5) for FC, yielding 35 possible combinations of outcomes at quality assessment. For CS, grade ‘E’ corresponds to carcasses that are the most well-muscled and therefore the most valuable, while for FC, grade ‘1’ corresponds to carcasses that are the leanest, but not necessarily the most valuable (see above).

Under the EUROP system, the ability to predict carcass quality while lambs are still on farm could be of substantial value to sheep producers, as it provides opportunities for selective breeding (Jopson et al., 2004) as well as adaptive farm management (Lambe et al., 2007; Brown et al., 2015) to attract higher premiums and reduce penalties. In recent years, computer tomography (CT) (Kongsro et al., 2008) and video image analysis (VIA) (Rius-

Vilarrasa et al., 2009; Einarsson et al., 2014) have both been successfully applied to predict carcass composition. Originally developed for semi-automated classification of post-slaughter carcasses, these technologies have since been extended to estimate fat and muscle densities of live animals (Clelland et al., 2014; Ibrahim, 2019). However, the specialist equipment required for these analyses is costly and hence generally unsuitable for commercial producers (Jones et al., 2004).

From the practical perspective, therefore, rudimentary techniques to predict carcass quality from physical parameters of live animals may carry greater promise across a diverse range of production systems. On-farm assessment of a lamb's carcass composition is typically conducted *in vivo* by a combined method of visual appraisal and condition scoring (Stanford et al., 1998), although subjective assessment of the hind-leg shape, an easier and less time-consuming protocol, has been suggested as an alternative method for overall carcass muscularity (Wolf et al., 2006). Nonetheless, these conventional approaches are primarily designed to provide information immediately prior to slaughter, a timing too late to influence management practices for the current cohort of animals.

In contrast, animal liveweight has the potential as an informative yet easy-to-measure indicator of a wide range of animal performance traits (McAuliffe et al., 2018a). It has long been established that different body tissues of livestock (organ, bone, muscle and fat) develop at different rates at each stage of physiological growth (Lonergan et al., 2019), with organ and bone maturing early, followed by muscle and finally fat. As this pattern is generally predictable and consistent, the overall shape of a lamb's growth curve has a clear impact on body composition at all ages, including carcass composition at slaughter (Hammond, 1952). In other words, lambs heavier at a given age can display a different pattern of tissue development, and ultimately carcass quality, to lambs lighter at the same age even when their genetic dispositions are similar to each other. As a case in point, carcass composition of previously feed-restricted animals has a significantly higher proportion of carcass fat when compared to feed-unrestricted animals, when the former group undergoes compensatory growth to reach slaughter weight at the same age (Oddy and Sainz, 2002). These findings notwithstanding, attempts to utilise such knowledge for commercial purposes have been limited to a small number of studies using mature lamb data (Stanford et al., 1998), and the relationship between a lamb's early development and final carcass grades is not currently well-understood.

The objective of the present study, therefore, was to test the hypothesis that a lamb's post-slaughter CS and FC can be predicted from liveweight information obtained at an early stage of physiological growth. As both quality scores are only observable in the form of discrete outcomes, a limited dependent variable framework was developed to estimate the probability of a young lamb subsequently realising each score and how this might change with on-farm interventions. The framework was then utilised to quantify the economic benefit of these interventions realised through increased carcass values.

## 4.2. Materials and methods

### 4.2.1. Flock management and data collection

The study site and associated flock management are described in depth within Chapter 2; the following paragraph contains information pertinent to this particular study.

The flock data originated from all three livestock farmlets of the NWFP, encompassing 2103 lambs that were born between 2011 and 2017 to a total of 860 ewes. Across the seven seasons the mean slaughter weight of lambs was 44.5 kg and the median lambing date was the 30$^{th}$ of March. The overall mortality rate of lambs was 2.58%, with 30.6% of these deaths occurring post-weaning (see Annex at end of thesis). The final dataset used in this study included lamb liveweights at birth, 4-weeks, 8-weeks, and 13 weeks (weaning). In addition, cross-matched dam data for ewe liveweight and body condition score (BCS) at lambing, weaning, and tupping were used interpret the findings in the discussion section.

### 4.2.2. Physical data analysis

For an explorative investigation of the relationship between post-slaughter CS/FC and early-life liveweight, analysis of variance (ANOVA) was initially conducted. Data were split into five groups (for CS) or seven groups (for FC) according to the realised carcass quality, and inter-group differences in liveweight were repeatedly tested using records from different timings post-weaning. This process was first implemented without fixed effects, and then duplicated by considering the potential impacts of year of production, sward type (permanent pasture, reseeded grass monoculture and reseeded legume/grass mix: see Chapter 2) and birth litter size.

The above approach, while intuitively attractive and statistically unbiased, fails to account for the direction of causality and therefore cannot directly quantify the impact of early-life liveweight on carcass quality. To overcome this issue, corresponding multinomial logit regression models were also estimated, with the aim to quantitatively associate a lamb's early weight to the probability of the animal achieving each CS/FC category. The same set of fixed effects were included in these estimations.

### 4.2.3. Economic analysis

To elucidate the potential financial benefit of manipulating farming systems to have different early-life liveweights, economic analysis was also carried out as part of this study. For this purpose, lambs were first allocated to three groups in equal proportions according to their weaning weights (‘light’, ‘medium’ and ‘heavy’). Realised mean carcass value within each group was then calculated using sales information received from the abattoir at the time of slaughter (current price method).

As these values are affected by price fluctuation in the market, a second set of carcass values were also calculated using a single date price for each CS/FC combination obtained from the Agriculture and Horticulture Development Board (constant price method). This process was conducted using multiple sets of price data, including those from the dates on which the 25$^{th}$ (early season), 50$^{th}$ (median) and 75$^{th}$ (late season) percentile lambs were slaughtered in different seasons. However, this choice was shown to have a minimal impact on inter-group variation in deadweight prices (see **Table 4.1** for an example from the 2017 grazing season) and therefore deemed unlikely to affect inter-group variation in carcass value either. For this reason, a single set of prices, for the median-finished lamb in the most recent year (2017), was arbitrarily selected for the constant price method.

The entire process was also repeated using alternative methods for light/medium/heavy grouping. As the results were again insensitive to the assumption (see **Table 4.2** for an example using lower and upper quartiles), the original rule of splitting the flock into equal thirds was retained. Finally, using the dataset thus prepared, inter-group differences in carcass value (under both current and constant prices) were evaluated based on the standard *t*-test.

All statistical analyses, including those described in the previous subsection, were conducted using R version 3.5.1 (R Core Team, 2020). An additional package 'mlogit' (Croissant, 2019) was used for multinomial logit regressions.

## 4.3. Results

### 4.3.1 Descriptive statistics of flock data

A summary of flock data used in the present study is given in **Table 4.3**. Notable differences in mean finishing age were observed across seven seasons, with a particular irregularity in 2012 and 2017. Both of these years are characterised by abnormal summer weather, either unusually wet (2012) or unusually dry (2017), resulting in limited pasture growth, slower lamb growth and thus reduced weaning weights. Although no such weather patterns were evident in 2015, the profitability of the system in this season was notably low. This phenomenon was primarily driven by market behaviour, as the UK saw the lowest deadweight prices for at least 5 years. This, in turn, caused an upward impact on slaughter weight, as lambs were finished later than usual to maximise the price benefit attained through heavier carcasses.

In the UK, the most common target carcass classification for domestically consumed lambs is R3L. These criteria were achieved or exceeded — commonly defined as CS/FC combinations of R3L, U3L, E3L, R2, U2 and E2 — by 92 % of lambs included in the present dataset (**Table 4.4**). It is acknowledged that CS/FC distributions shown here are not necessarily representative of the whole of the UK, where only 57 % of carcasses meet the specification, as the study farm is located in a lowland area with relatively high-quality pasture and also receives a relatively high level of labour input (Takahashi et al., 2018). In this regard, the present research should be seen as a feasibility study using a single set of high-resolution single-farm data; the applicability of findings to different farming systems that will have a wide range of CS/FC distributions will be discussed at the end of the chapter.

### 4.3.2. Physical data analysis

The results of explorative ANOVA showed a significant difference in weaning weight between CS groups ($p < 0.001$), with heavier animals associated with better conformation (**Figure 4.1a)**. This difference was evident even after the year of production, sward type and birth litter size were each accounted for as fixed effects ($p < 0.001$). A similar result was also observed between FC groups ($p < 0.001$ with and without fixed effects), with higher weaning weights associated with leaner meat (i.e. a lower FC) (**Figure 4.1b**).

Both relationships sustained when weaning (13-week) weight was replaced with 15-week liveweight, indicating the robustness of the above finding. As the season progressed, however, more animals satisfied the slaughtering criteria and thus were removed from the sample, imposing a selection bias to the dataset (Supplementary **Figure 4.S1**). Likely due to this change, equally strong patterns were no longer observed from data collected at 17 weeks onwards (**Supplementary Figure 4.S2**).

The results of multinomial regressions supported the causal relationships identified through ANOVA, with a lamb's weaning weight predicting the probability distribution for its subsequent carcass classification in a statistically significant manner. For a CS model using the score R as the baseline, an increase in weaning weight was positively associated with scores E ($p = 0.008$) and U ($p = 0.001$) (**Supplementary Table 4.S1**). For a FC model using the score 3L as the baseline, an increase in weaning weight was positively associated with a score of 2 ($p < 0.001$), and negatively associated with a score of 3H ($p = 0.03$) (**Supplementary Table 4.S2**).

Across both models, all statistically insignificant ($p > 0.05$) coefficients (conformation score O and fat classes 1, 4L and 4H) were related to outcomes with low observed frequencies (**Table 4.4**).

### 4.3.3. Economic analysis

A comparison of flock data between the three groups defined by weaning weight confirmed the expectation that lambs in 'heavy' group (at weaning) required a significantly shorter time to finish than 'medium' group lambs ($p < 0.001$), which, in turn, required a significantly shorter time to finish than 'light' group lambs ($p < 0.001$) (**Table 4.5**). The proportion of animals remaining on the farm after the 1st of October each year, roughly the timing when the pasture requirement for ewes increases for next reproduction, was significantly lower in the 'heavy' group compared to both 'medium' and 'light' groups.

There was a significant inter-group difference in the final economic value of lambs ($p < 0.001$ based on multi-sample *F*-test) when the current prices were applied. Carcasses from 'heavy' lambs were most valuable, with the average carcass value £3.57 higher than 'medium' lambs ($p < 0.001$). Carcasses from 'light' lambs were the least valuable, with the average value £1.21 lower than 'medium' lambs ($p = 0.006$). As the current value of a carcass reflects the seasonal variation in market price, the higher value of 'heavy' lambs was not only attributable to quality premium paid for improved CS/FC but also to favourable prices they attracted as a result of finishing earlier in the season.

When the effect of price fluctuation was eliminated by applying the constant price, no significant difference was observed between carcass values of 'light' and 'medium' lambs ($p = 0.83$). However, a significant difference remained between carcass values of 'medium' /

'light' and 'heavy' animals ($p < 0.001$), with the 'heavy' group worth £1.71 more than 'medium' group. This result suggests that approximately half of the value difference between 'medium' and 'heavy' lambs is directly explained by physical difference in carcass quality, with the remainder indirectly through seasonal price variation.

## 4.4. Discussion

### 4.4.1. Predictability of carcass scores

The output from the multinomial models suggests that lambs which grow faster early in their lives are more likely to have leaner and more muscular carcasses when they reach the finishing weight. Availability of these predictive methods offers greater opportunities for effective flock management, where animals with either large expected premiums (for selective breeding) or large expected penalties (for adaptive management) could be segregated for bespoke grazing and supplementation strategies. To the best of my knowledge, this is the first study to quantify the impact of a lamb's early-life performance on carcass quality. However, the finding here is consistent with an already known relationship that links the stage of body growth to the composition of newly acquired tissues in domestic livestock.

Tissue development of these young animals can be simplified into four distinct phases (Lonergan et al., 2019). Shortly after birth, organs, bones, and muscle all develop rapidly but with minimal fat growth (first stage). As the animal's body broadens, organ and bone approach maturity, allowing enhanced muscle development and initial formation of fat reserves (second stage). These reserves then start to increase rapidly while muscle also continues to grow (third stage). Finally, as mature weight is approached, muscle growth sharply slows down as the animal builds extra fat as energy reserves (fourth stage).

Consequently, lambs heavier at weaning are more likely to reach the target weight while still in an earlier stage of tissue development, resulting in a higher proportion of muscle and a lower proportion of fat in carcasses (**Figure 4.2a**) compared to those lighter at weaning (**Figure 4.2b**). A further analysis of lifetime growth data to compare ‘high-quality’ animals (eventually scoring E2) and ‘low-quality’ animals (O3L) also supports this hypothesis (**Supplementary Figure 4.S3**), with slopes of growth curves resembling respective conceptual representations (**Supplementary Figures 4.S2a and 4.S2b)**.

### 4.4.2. Economic implications

It is well-established that selecting ram breeds with more favourable carcass characteristics is an effective way of improving lamb carcass quality (Jones et al., 2004; Lambe et al., 2008; Álvarez et al., 2013). However, farming systems unsuited to a change of breed, or systems already using an optimal breed type are unable to realise this potential. In such cases, the finding from the present research may offer an alternative pathway to improve carcass quality and, in turn, system-level efficiency and profitability. Importantly, lambs heavier at weaning were more likely to result in higher-value carcasses when slaughtered, even when constant prices independent of seasonal variations were applied. This indicates that the difference in carcass values observed between different weaning weight groups was at least partially attributable to physical quality of carcasses.

To investigate the economic impact purely arising from this relationship, an auxiliary simulation was conducted using the multinomial models estimated above. For each lamb, the probability of achieving each combination of carcass scores (CS and FC) was calculated for three scenarios: actual weaning weights (baseline), baseline + 6.75 kg and baseline + 13.25 kg. The increments used for the latter two scenarios respectively corresponded to the interquartile range and the 90 % range of weaning weights within the dataset, and thus were considered to be realistic. The derived set of probabilities was then used to calculate the expected value of the carcass for each scenario under constant prices and these values were aggregated for the entire dataset.

As expected, enhanced weaning weights were associated with an increased chance of observing higher (better) CS and lower (leaner) FC, with the second and third scenarios resulting in mean carcass values 23 and 44 pence above the baseline, respectively (**Figure 4.3**). Across the whole dataset, the FC model was more sensitive to the weaning weight than the CS model. Nevertheless, few animals were predicted to have FC of 1, generally considered to be too lean to attract a price premium even under enhanced weaning weights. This result suggests that the risk of 'over-fattening' young animals is relatively low. It should be noted that the constant prices used in this model have a wider spread across CS than FC: for example, the difference in premium between FC of 2 and 3L (1.4 pence) is substantially lower than that between CS of U and R (10.4 pence). When the market places a stronger emphasis on FC, therefore, the economic impact of early life development could be greater.

In addition, achieving a higher weaning weight is likely to bring several indirect economic benefits that are not captured in the form of improved carcass quality. As alluded to above, faster growing lambs heavier at weaning are more frequently finished at an earlier point in the season and deadweight prices normally peak around the end of June — roughly the average weaning time for spring-born lambs. As can be seen in **Table 4.5**, this price fluctuation can have a considerable impact on overall carcass value, as heavy-weaned lambs were typically finished during this period of undersupply.

Faster finishing lambs are also known to be more cost efficient, regardless of carcass quality or seasonal variation in price. Assuming similar inputs per day, lambs which reach finishing age faster have lower accumulated maintenance energy and higher feed efficiency, leading to reduced feed costs (Keady and Hanrahan, 2006). Even in low-input systems where pasture growth is often not directly associated with financial outlays, reduced time to slaughter is associated with lower likelihood of disease, parasitism and lameness, leading to a decrease in veterinary costs (Gascoigne and Lovatt, 2015).

At the farming-systems level, there is a potential impact on pasture utilisation rate that should not be overlooked (Bohan et al., 2018). As can be seen in **Table 4.5**, less than 4 % of heavy-weaned lambs were remaining on farm after the 1st of October, approximately the beginning of the next reproduction season in lowland systems, compared to nearly 70% of light-weaned lambs. Ewe nutrition is particularly crucial at this point in the season due to the association between ewe condition at tupping and fertility (Kenyon et al., 2014), and also between ewe condition at tupping and ewe condition at lambing (Gascoigne and Lovatt, 2015). Ewe condition at lambing, in turn, is strongly associated with pre-weaning lamb growth in the following season (Mathias-Davies et al., 2011). Having fewer lambs remaining on the farm in the autumn, therefore, reduces resource competition and allows better pasture availability for ewes, which rear faster growing lambs with shorter finishing times and better carcass quality, to create a continuous pathway to improve the efficiency of the entire production cycle over multiple seasons. Ultimately, this change will provide an opportunity to increase the optimal stocking density — here measured by the number of breeding ewes per area — a major driver of farm-level profitability (Earle et al., 2017).

### 4.4.3. General discussion

While the relationship between a lamb's early-life weight and carcass quality has not been previously identified, this finding does not result in producer benefit unless the animal's early-life performance can be manipulated either by selection or intervention. To this end, supplementing young lambs with creep feed is a reliable approach for improving growth rates early in their lives (Keady, 2010), perhaps more so than supplementing ewes during early lactation (Campion et al., 2017). Nonetheless, the impact of such 'forced' growth on subsequent tissue development is not well-understood and, as animals used in this study received no supplementation and were finished entirely off pasture as part of system-scale research (McAuliffe et al., 2020), the present dataset is unable to assess this matter further. On the other hand, this research design did allow the maintenance of a 'natural' nutrient flow from ewes to lambs, and reiterate that focussing on ewes' body condition during pregnancy may be a cost-effective way of improving lamb growth and consequently carcass value (Kenyon et al., 2014). Although outside the main scope of this study, a correlation analysis of matched data indicated a strong association between the ewe's body condition score at lambing and the pre-weaning growth rate of her lambs ($p < 0.001$).

Finally, it is acknowledged that all lambs from this study were of a comparable breed type, and although presenting a representative snap-shot of a typical low-land sheep enterprise in the UK, not all findings may be immediately translatable to the entire sheep industry. In particular, breed type can have a significant impact on carcass composition (Wood et al., 1980) and, in some cases, even influences the optimal stage of skeletal development for slaughter (Lambe et al., 2007). As mixed-breed enterprises are unsuitable for system-scale research with a limited number of farms, lower-resolution data from an extensive network of commercial farms are likely to provide the best platform to investigate this issue.

**Table 4.1.** Summary of flock data

| Year | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | Mean |
|---|---|---|---|---|---|---|---|---|
| Ewe data | | | | | | | | |
| Age at lambing (years) | 4.20 ±0.134 | 4.49 ±0.147 | 4.00 ±0.115 | 3.59 ±0.095 | 4.00 ±0.073 | 4.75 ±0.072 | 5.59 ±0.072 | 4.26 ±0.045 |
| Birth litter size | 2.00* | 2.06 ±0.025 | 2.01 ±0.040 | 2.03 ±0.048 | 1.96 ±0.036 | 2.08 ±0.043 | 1.97 ±0.037 | 2.01 ±0.014 |
| Median lambing date | 28-Mar | 30-Mar | 31-Mar | 29-Mar | 30-Mar | 30-Mar | 01-Apr | 30-Mar |
| Lamb data | | | | | | | | |
| Total lambs finished | 274 | 266 | 235 | 258 | 338 | 360 | 372 | 300 |
| Carcass value (£) | 77.2 ±0.30 | 65.6 ±0.45 | 74.2 ±0.63 | 66.3 ±0.50 | 60.9 ±0.27 | 74.8 ±0.32 | 75.9 ±0.28 | 70.8 ±0.19 |
| Slaughter age (days) | 143 ±1.7 | 198 ±1.8 | 141 ±2.3 | 157 ±2.3 | 145 ±2.0 | 165 ±2.1 | 180 ±1.9 | 162 ±0.9 |
| Birth weight (kg) | *na* | *na* | *na* | 5.41 ±0.06 | *na* | 5.22 ±0.05 | 5.18 ±0.05 | 5.26 ±0.02 |
| Weaning weight (kg) | 35.6 ±0.30 | 30.3 ±0.27 | 33.5 ±0.28 | 33.6 ±0.28 | 34.8 ±0.27 | 33.5 ±0.27 | 31.5 ±0.23 | 33.3 ±0.11 |
| Finishing weight (kg) | 44.8 ±0.15 | 44.7 ±0.18 | 43.4 ±0.15 | 44.2 ±0.16 | 45.0 ±0.12 | 44.7 ±0.12 | 44.4 ±0.10 | 44.5 ±0.05 |

Mean value and standard error for each year unless stated otherwise

* Only twin-bearing ewes were selected for the initial year of the trial, hence lack of variation in litter size

**Table 4.2.** Spread of carcass quality classifications

| | | Fat class | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3L** | **3H** | **4L** | **4H** | **5** | **Total** |
| Conformation score | **E** | 0 (0%) | 8 (0.38%) | 49 (2.33%) | 10 (0.48%) | 5 (0.24%) | 0 (0%) | 0 (0%) | 72 (3.42%) |
| | **U** | 0 (0%) | 147 (6.99%) | 415 (19.73%) | 42 (2.00%) | 2 (0.10%) | 1 (0.05%) | 1 (0.05%) | 608 (28.91%) |
| | **R** | 7 (0.33%) | 571 (27.15%) | 738 (35.09%) | 45 (2.14%) | 5 (0.24%) | 1 (0.05%) | 0 (0%) | 1367 (65.01%) |
| | **O** | 8 (0.38%) | 34 (1.62%) | 14 (0.67%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 56 (2.66%) |
| | **P** | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |
| | **Total** | 15 (0.71%) | 760 (36.14%) | 1216 (57.67%) | 97 (4.61%) | 12 (0.57%) | 2 (0.10%) | 1 (0.05%) | 2103 (100%) |

**Table 4.3.** Economic implications of weaning weight

| | Weaning weight group | | |
|---|---|---|---|
| | Light (< 31kg) | Mid (>31kg & < 35kg) | Heavy (> 35kg) |
| Mean slaughter age | 196 days | 165.3 days | 129.2 days |
| % remaining on farm after October 1st | 69.16% | 27.63% | 4.65% |
| Mean carcass value (actual price paid) | £68.48 | £69.69 | £73.26 |
| Mean carcass value (at constant price)* | £72.96 | £72.88 | £74.59 |

* As evaluated with lamb deadweight prices from 07/10/2017 (median finishing date)

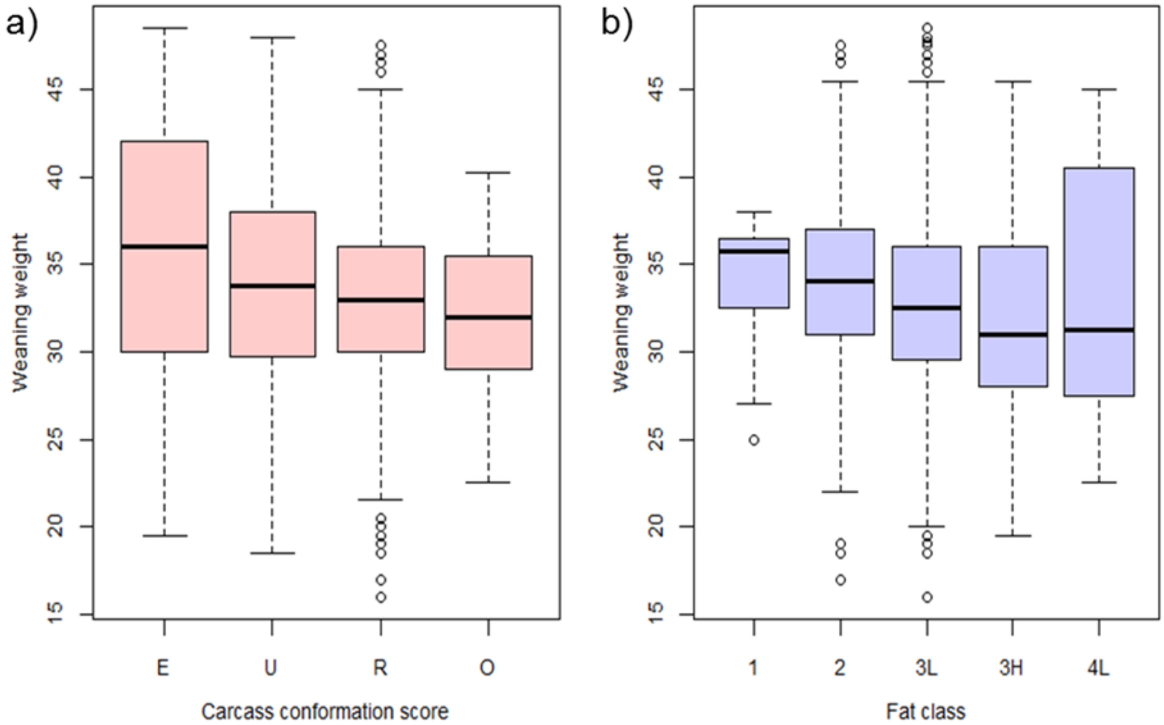


**Figure 4.1.** Conditional boxplots for weaning weight. A significant difference in weaning weight (kg) was observed between different carcass conformation score groups ($p < 0.001$) (**a**) and between different fat class groups ($p < 0.001$) (**b**) at slaughter.

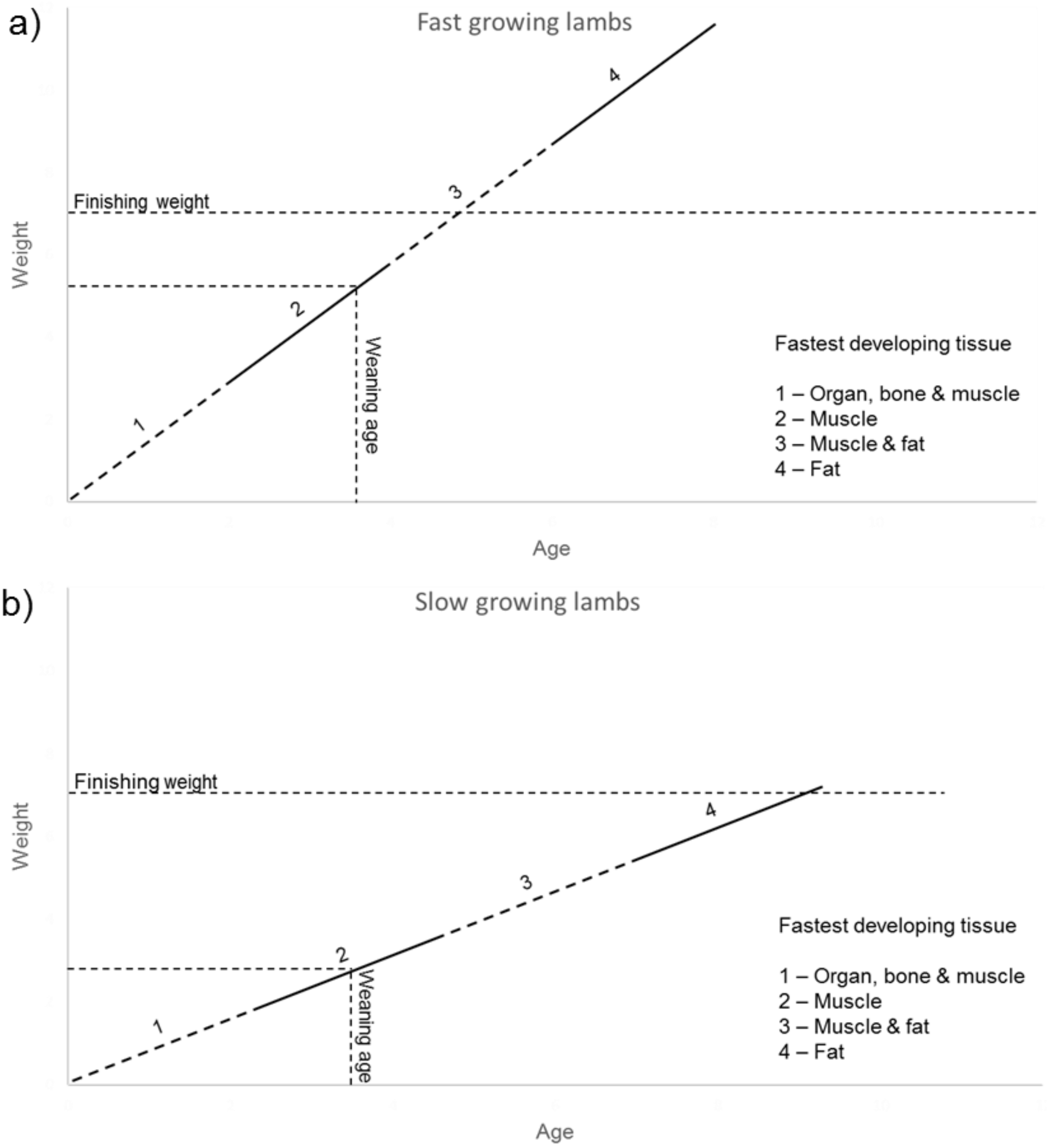


**Figure 4.2.** Physiological development of lambs inferred from the present study. Different tissues develop at alternate stages, with organ, bone and muscle developing rapidly in early life (1), followed by muscle (2), muscle and fat (3) and finally fat only (4) as mature weight is approached. Faster growing lambs reach finishing weight while still in an earlier stage of tissue development (**a**), resulting in a larger proportion of the carcass composed of muscle than in slower growing lambs (**b**). Straight lines are used for clarity; actual growth curves are likely to be nonlinear.

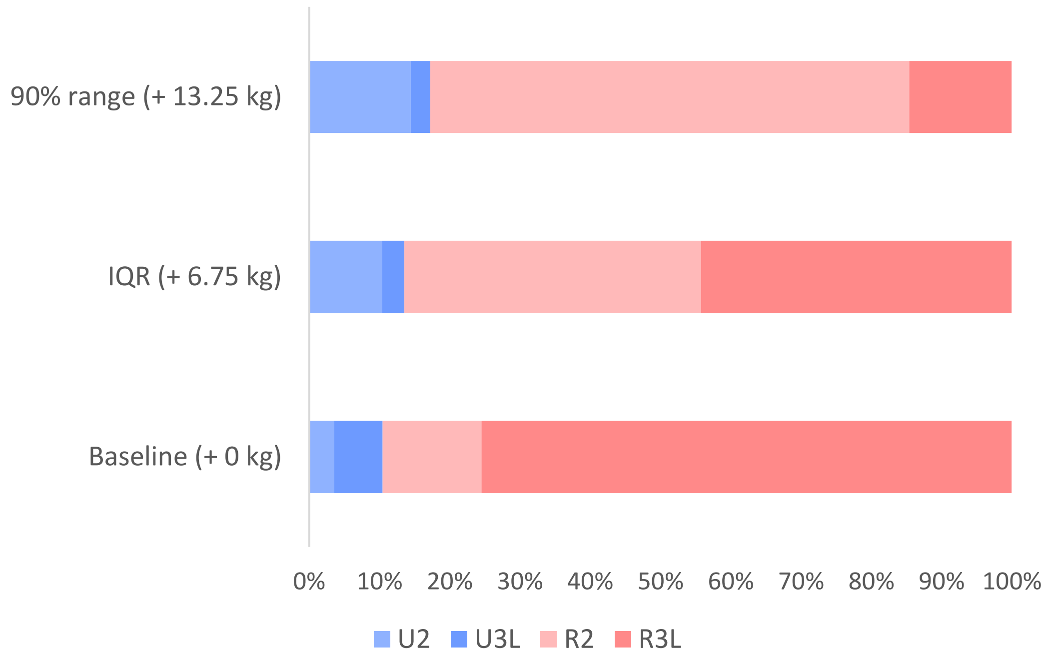


**Figure 4.3.** Predicted changes in carcass score under enhanced weaning weight. When weaning weight becomes heavier by 13.25 kg, the likelihood of the animal attaining the fat class of 2 was found to increase dramatically (from *n* = 364 to *n* = 1708). The effect on likelihood of the animal attaining the conformation score of U, on the other hand, was only moderate (from *n* = 216 to *n* = 356).

## Appendix to Chapter 4.

**Table 4.S1.** Seasonal variation in sheep deadweight prices (pence/kg) during 2017

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Yearly mean | | 1 | 2 | 3L | 3H | 4L | 4H | 5 |
| | E | 424.6 | 448.5 | 447.5 | 430.6 | 411.2 | 387.9 | 350.2 |
| | U | 423.8 | 442.4 | 441.5 | 429.6 | 408.0 | 384.5 | 352.6 |
| | R | 413.7 | 432.1 | 431.0 | 424.7 | 409.7 | 386.1 | 353.8 |
| | O | 378.8 | 413.1 | 417.4 | 414.8 | 410.1 | 389.5 | 331.0 |
| | P | 295.1 | 303.7 | 298.4 | 287.5 | - | - | - |
| 1st quartile slaughtered lamb | | 1 | 2 | 3L | 3H | 4L | 4H | 5 |
| | E | 393.3 | 421.7 | 418.6 | 400.5 | 383.1 | 354.2 | 322.5 |
| | U | 398.3 | 416.0 | 413.0 | 400.9 | 378.4 | 359.3 | 320.0 |
| | R | 387.9 | 407.7 | 406.3 | 399.6 | 383.3 | 363.0 | 326.2 |
| | O | 350.4 | 393.5 | 399.6 | 390.6 | 383.9 | 363.9 | 325.0 |
| | P | 334.9 | 303.9 | 302.7 | - | - | - | - |
| Median slaughtered lamb | | 1 | 2 | 3L | 3H | 4L | 4H | 5 |
| | E | 376.7 | 404.7 | 404.6 | 387.1 | 363.2 | 343.8 | 310.0 |
| | U | 375.4 | 396.9 | 395.9 | 384.6 | 361.6 | 337.3 | 304.9 |
| | R | 367.9 | 386.2 | 384.4 | 378.1 | 365.2 | 344.2 | 308.7 |
| | O | 342.2 | 365.9 | 368.1 | 368.7 | 370.1 | 368.7 | 310.0 |
| | P | 267.9 | 262.0 | 248.3 | - | - | - | - |
| 3rd quartile slaughtered lamb | | 1 | 2 | 3L | 3H | 4L | 4H | 5 |
| | E | 375.0 | 413.1 | 410.1 | 391.6 | 366.9 | 327.0 | - |
| | U | 380..6 | 404.6 | 401.2 | 388.2 | 362.1 | 335.3 | 293.3 |
| | R | 369.5 | 391.6 | 389.7 | 381.1 | 365.5 | 340.5 | 306.4 |
| | O | 324.1 | 366.1 | 371.0 | 370.0 | 368.6 | 348.2 | 300.0 |
| | P | 265.0 | 283.6 | 265.0 | - | - | - | - |

**Table 4.S2.** Carcass value of lambs (pence/kg) split by weaning weight (25%/50%/25%)

| | Median slaughtered lamb | Lower quartile | Upper quartile | Annual mean | Actual value of NWFP lambs |
|---|---|---|---|---|---|
| Light | 387.4 | 405.8 | 392.2 | 433.2 | 362.9 |
| Medium | 387.1 | 407.1 | 392.1 | 433.0 | 369.2 |
| Heavy | 389.3 | 408.3 | 394.7 | 435.1 | 386.0 |

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**Table 4.S3.** Carcass value of lambs (pence/kg) split by weaning weight (33%/33%/33%)

| | Median slaughtered lamb | Lower third | Upper third | Annual mean | Actual value of NWFP lambs |
|---|---|---|---|---|---|
| Light | 387.6 | 406.0 | 392.5 | 433.2 | 363.3 |
| Medium | 387.3 | 407.4 | 392.3 | 433.1 | 370.4 |
| Heavy | 388.9 | 407.9 | 394.0 | 434.4 | 382.1 |

**Table 4.S4.** Coefficients from multinomial logit regression for conformation score

| | E | U | O |
|---|---|---|---|
| Weaning weight | 0.075** | 0.036** | -0.038 |
| Grass clover lay | 0.520 | 0.082 | 0.471 |
| Perennial ryegrass lay | 0.573 | -0.067 | -0.306 |
| 2012 | -20.015 | -1.243*** | 0.529 |
| 2013 | -0.807. | -1.148*** | 1.342. |
| 2014 | -20.627 | -1.577*** | 1.709* |
| 2015 | -2.117*** | -0.984*** | -17.792 |
| 2016 | -1.637** | -0.785*** | 0.270 |
| 2017 | -1.178* | -0.836*** | 0.551 |
| Birth litter size = 1 | 0.824. | 0.197 | -0.357 |
| Birth litter size = 3 | -0.364 | -0.002 | -0.011 |
| | | | |
| Marginal effect* | 0.002 | 0.006 | -0.002 |

Significance codes: *** 0.001, ** 0.01, * 0.05, . 0.1.
Fixed effect baseline variables: Permanent pasture, 2011 and Birth litter size = 1
Output baseline variable: R

* Change in average probability across the entire sample when weaning weight is increased by 1 kg from the actual value

**Table 4.S5.** Coefficients from multinomial logit regression for fat class

| | 1 | 2 | 3H | 4L | 4H |
|---|---|---|---|---|---|
| Weaning weight | 1.024 | 7.705*** | -5.407* | -4.452 | 2.498 |
| Grass clover lay | 6.992 | -3.607* | 9.855* | 1.263 | 1.712 |
| Perennial ryegrass lay | 8.921 | -2.888. | 3.941 | -1.401 | -3.060 |
| 2012 | 5.739 | 5.679** | -1.354** | -1.975 | -3.192 |
| 2013 | 1.872 | -3.125 | -6.986 | -1.970 | -3.340 |
| 2014 | 2.008 | 7.422*** | -1.750** | -2.314 | -5.074 |
| 2015 | 1.751 | -2.566 | -1.446** | -2.314 | -5.074 |
| 2016 | 1.875 | -5.975 | -1.078* | -1.126 | -3.266 |
| 2017 | 1.879 | 1.019 | -8.237. | -1.723 | -5.054 |
| Birth litter size = 1 | -2.162 | -1.234*** | 9.859** | -1.975 | 1.836 |
| Birth litter size = 3 | -1.118 | 2.436. | -2.608 | -1.867 | -2.011 |
| | | | | | |
| Marginal effect* | < 0.001 | 0.017 | -0.003 | < 0.001 | < 0.001 |

Significance codes: *** 0.001, ** 0.01, * 0.05, . 0.1.
Fixed effect baseline variables: Permanent pasture, 2011 and Birth litter size = 1
Output baseline variable: 3L

* Change in average probability across the entire sample when weaning weight is increased by 1 kg from the actual value

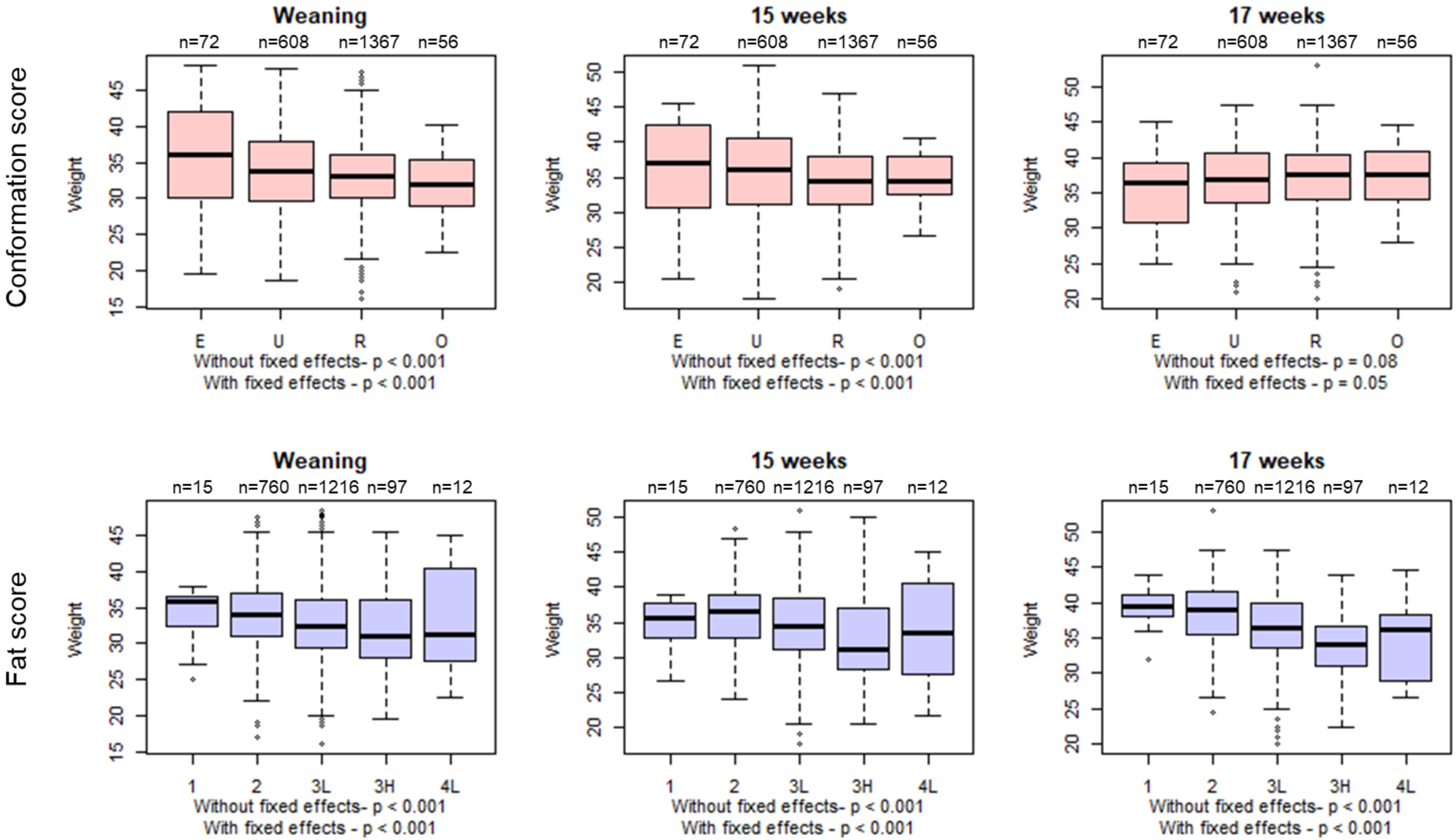


**Figure 4.S1.** Relationship between carcass quality measures and early-life liveweight at three different ages.

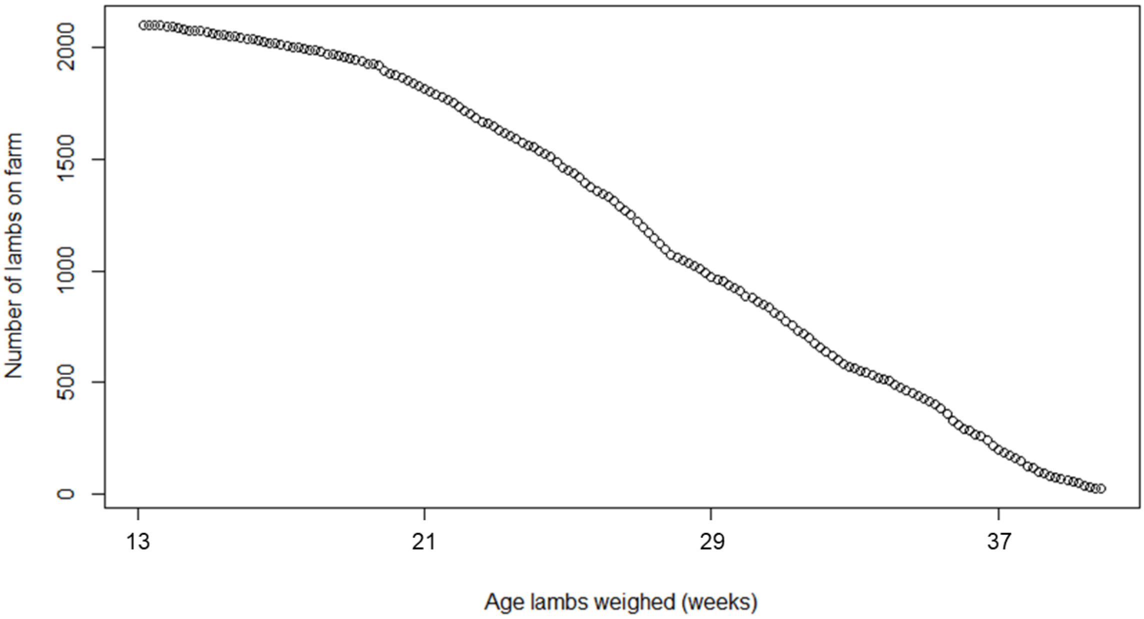


**Figure 4.S2.** Population dynamics on the farm due to removal of finished lambs.

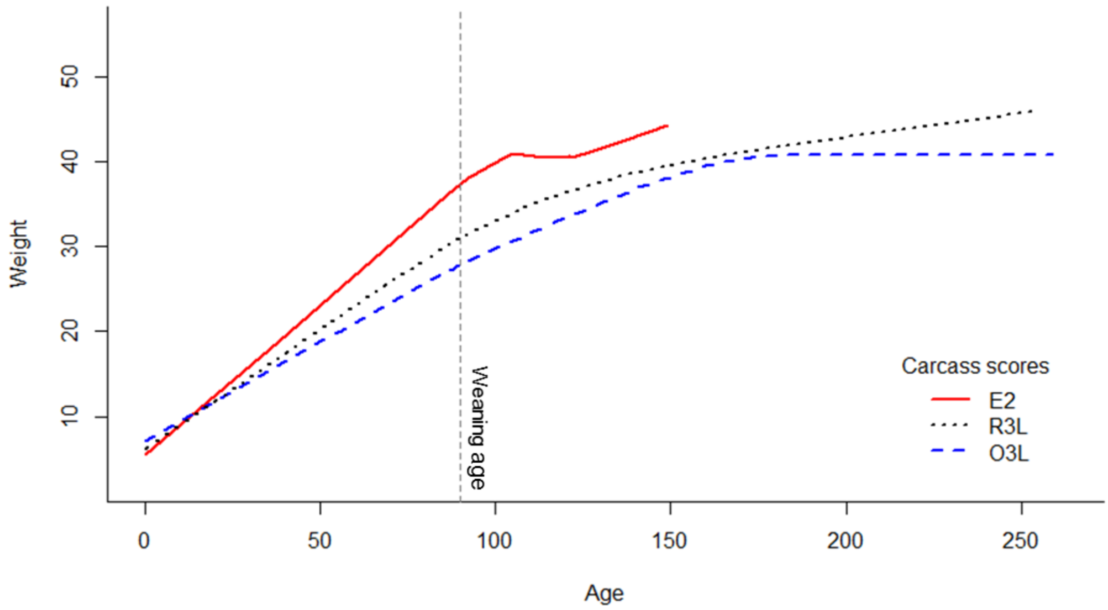


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**Figure 4.S3.** Growth rates of lambs split by carcass quality. These curves follow similar patterns to those predicted in **Figure 4.2**. Lambs with high-quality carcasses (E2, *n* = 8) grew faster in early development and hence is represented by a steeper growth curve. Lambs with the most common carcass score (R3L, *n* = 728) and particularly those with low-quality carcasses (O3L, *n* = 14) were represented by flatter growth curves.

# Chapter 5. Quantifying the value of on-farm measurements to inform the selection of key performance indicators for livestock production systems

## Summary

The use of key performance indicators (KPIs) to assist on-farm decision making has long been seen as a promising strategy to improve operational efficiency of agriculture. The potential benefit of KPIs, however, is heavily dependent on the economic relevance of the metrics used, and an overabundance of ambiguously defined KPIs in the livestock industry has disincentivised many farmers to collect information beyond a minimum requirement. Using high-resolution sheep production data from the North Wyke Farm Platform (NWFP), a system-scale grazing trial in southwest United Kingdom, this chapter proposes a novel framework to quantify the information values of industry recommended KPIs, with the ultimate aim of compiling a list of variables to measure and not to measure. The results demonstrated a substantial financial benefit associated with a careful selection of metrics, with top-ranked variables exhibiting up to 3.5 times the information value of those randomly chosen. When individual metrics were used in isolation, ewe weight at lambing had the greatest ability to predict the subsequent lamb value at slaughter, surpassing all mid-season measures representing the lamb's own performance. When information from multiple metrics was combined to inform on-farm decisions, the peak benefit was observed under four metrics, with inclusion of variables beyond this point shown to be detrimental to farm profitability regardless of the combination selected. The framework developed herein is readily extendable to other livestock species, and with minimal modifications to arable and mixed agriculture as well.

## 5.1. Introduction

Against the backdrop of rapid population growth and economic development, worldwide demand for animal source foods (ASF) continues to increase (Alexandratos and Bruinsma, 2012; van Kernebeek et al., 2016). ASF play an important role in human nutrition as a source of high-quality protein and essential micronutrients, both of which are biologically difficult and economically costly to obtain from plant source foods alone (Murphy and Allen, 2003; Mottet et al., 2017; Willett et al., 2019b). However, agricultural systems to produce ASF are generally associated with lower land use efficiency compared to alternative land use (van Zanten et al., 2016), making their areal expansion neither economically feasible nor socially desirable (Foley et al., 2011; van Zanten et al., 2018; Wilkinson and Lee, 2018). Increased demand for ASF therefore can only acceptably be met through improvements in land use efficiency of existing livestock systems (FAO, 2011; Garnett et al., 2017; Kamilaris et al., 2019), or by filling the 'yield gap' between current production and the best potential production (Godfray et al., 2010). The presence of a substantial variability in production efficiency is widely recognised across the livestock industry (Dijkstra et al., 2013), even within systems operating under comparable climatic, biophysical and socioeconomic conditions (Curry, 2002). Importantly, this is the case at both the farm scale (Jones et al., 2014) and the animal scale (McAuliffe et al., 2018b), with economic and environmental performances often positively correlated with one another regardless of the spatial resolution (Hyland et al., 2016; McAuliffe et al., 2017). Thus, an effort to reduce the yield gap suffered by less efficient farm systems and less efficient animals are equally likely to enhance the industry's capability for ASF provision.

As a means of decision support to facilitate this transformation, two interrelated frameworks have primarily been adopted in the farm management literature: benchmarking and identification of KPIs. Of the two, the concept of benchmarking centres on a comparison of an individual farm's performance against an externally defined standard, normally derived from a survey of comparable enterprises (Kahan, 2005; Ryan et al., 2016). As such, this approach provides farms with a way to assess how efficiently their business is operating on a relative scale (Franks and Haverty, 2005). However, most benchmarking exercises take the form of whole business analysis based on aggregate measures rather than information arising from individual production processes, often resulting in output metrics that are not necessarily informative for day-to-day operation when used in isolation (Soteriades et al., 2016). A 5-year study of pork enterprises in Iowa, US found that only 6% of sample farms were consistently ranked within the top-third in terms of profitability, while 67% were ranked in the bottom-third at least once (Lawrence et al., 1998). This example demonstrates that an attempt to emulate exemplary on-farm practices from aggregated measures can be problematic, especially given that the method's capability to identify the presence of an issue is not always accompanied by a solution (Fleming et al., 2006).

KPIs, on the other hand, are generally defined as variables closely related to production inputs, production outputs or production efficiency, selected with a higher-level goal of understanding the drivers behind an individual farm's performance (Wilson, 2005). A study evaluating the Norwegian dairy sector employed a principal components analysis (PCA) to simultaneously identify financial and production factors contributing to gross margin, and then used this information to determine on-farm practices that should be promoted (Hansen et al., 2005). Another study in New Zealand quantified the level of resilience embedded into dairy farms through variables strongly associated with inter-farm variability, and from this information produced a list of target KPIs for low-performing farms to measure and thus improve (Shadbolt et al., 2013). In a study designed to determine KPIs for the income of Australian wool producers, the technical efficiency of farms was first estimated and then the data analysed through a PCA to identify production factors associated with maximum technical efficiency (Geenty et al., 2006). These farm-scale studies were explicitly designed to explore precision agriculture solutions for efficiency-related issues currently present within each flock/herd, thereby ultimately increasing the overall competitiveness of the local livestock industry.

The potential benefit of KPIs, however, is heavily dependent on the relevance of the variables to be used (Hansen et al., 2005; Kahan, 2005; Rivas et al., 2019). The number of livestock industry recommended KPIs has steadily increased since the agricultural intensification of the 1960s (Ronan and Cleary, 2000), leading to a high level of duplication across a long list of variables (AHDB, 2019b). This, in turn, has invited uncertainty around the exact purpose of KPI measurements, both in general and in particular to individual metrics, frequently resulting in a practically unconstructive message of ‘measure as much as you can’ without due comprehension of scientific rationales. Critically, on-farm performance monitoring requires considerable cost, time and resources (Franks and Collis, 2003) yet offers no guarantee of benefit (Franks and Haverty, 2005); thus, such ambiguity around the meaning of KPIs can easily disincentivise farmers to collect any production data at all.

Using high-resolution sheep monitoring data from the NWFP, a system-scale grazing trial in Devon, UK (Orr et al., 2016), this chapter aims to develop a novel quantitative framework to evaluate the information value of various performance indicators on a livestock farm’s short-term economic performance. The UK sheep sector presents a unique and suitable case exemplar for the present study; despite its economic scale (£2.5 billion p.a.) and an extensive list of recommended KPIs made available to farmers (AHDB, 2019b), it is known for an exceptionally low level of production performance monitoring (Kaler and Ruston, 2019). In the past, this phenomenon has primarily been attributed to a heavy reliance on agricultural subsidy payments (Thompson, 2009), which reduces the need for in-depth analysis of on-farm income and expenditures (Kaler and Green, 2013). However, the sector is predicted to be one of the most severely affected by the UK's withdrawal from the European Union, and therefore improvement in productivity is urgently needed (Hubbard et al., 2018).

The present case study will adopt end-of-season variables of slaughter age (days required to reach the target weight) and realised carcass value as short-term animal-level measures of economic performance. These variables represent the cost and revenue of the enterprise, respectively, and are known to be driving factors of UK sheep farms' profitability (Croston and Pollott, 1994; Bohan et al., 2019; Lima et al., 2020). The information value of a mid-season variable, or a performance indicator, will then be quantified in relation to the strength of its association with end-of-season measures and, based on this value, the relative usefulness of multiple indicators will be evaluated. The general framework has been designed to accommodate a wider range of performance indicators, for example at different spatial resolutions and from other livestock sectors, providing an evidence base to support farmers' decisions on what to measure and what not to measure.

## 5.2. Methods

### 5.2.1. Definitions of terminology

The aforementioned ambiguity about KPIs is likely to have stemmed, at least partially, from the fact that existing lists of variables indistinguishably include those that describe a farm's enterprise structure, management strategies and performance, with no explicit recognition given to their interrelationships. To overcome this issue, variables commonly referred to as KPIs were first categorised into the following three groups prior to the quantitative analysis. As will be discussed, each group has a specific role in the subsequent computational process to calculate the redefined KPI values.

*Predictors* are defined as variables that do not directly represent the ultimate performance of the enterprise but are useful for its estimation. Akin to leading indicators in economics (Allen, 1994), an example of a predictor is the eight week weight of lambs; it does not equate to any financial value at the time of measurement but is strongly (although imperfectly) associated with finishing age which, in turn, affects production cost. Predictors are generally most useful for informing short-term decisions for adaptive farm management, for instance whether to provide supplementary feed, as this information can be collected before production of the final output.

*Outcomes*, on the other hand, are more directly linked to the ultimate performance of the enterprise, akin to lagging indicators in economics (Burkholder, 1980). To continue the previous example, the finishing age of lambs can be seen as an outcome variable, as the causal relationship between this metric and profitability is almost certain. Unlike predictors, these variables are unhelpful for informing decisions about short-term changes, as the relevant information is collected after production is realised. They are, however, useful at long-term decision making across multiple seasons, as historic information in this form can be used to determine the optimal enterprise structure given the farm’s biophysical, financial, and labour constraints.

The final category, *system descriptors*, is composed of variables that are frequently referred to as KPIs but more closely represent long-term strategic decisions taken by farm managers themselves. Ewe to ram ratio, for example, is often considered a KPI but is almost always a direct result of a human choice. Akin to diagnostic measures in economics (Badawy et al., 2016), system descriptors affect operation of the farm through multiple pathways and therefore likely have indirect impacts on its overall performance as well. However, they are of less importance as an indicator to assist adaptive decisions and should instead be seen as a set of constraints, or a rule of engagement, under which all other decisions are optimised in the short-term.

Based on the above definitions, KPIs currently in common usage by the livestock industry have been reclassified in **Table 5.1**. As discussed, the analytical framework proposed in this study was designed to select variables of which measurements should be prioritised to support a farm’s short-term decisions. In line with this goal, only *predictors* will be considered as performance indicators henceforth, with the view to identify those with high information values as redefined ‘key’ performance indicators vis-à-vis conventional ‘KPIs’. The information values of predictors will be quantified in relation to their capability to predict *outcomes* under a given set of *system descriptors*.

### 5.2.2. Case study of the UK sheep sector — data

This case study was conducted at the NWFP, which is described in depth within Chapter 2; The following paragraph contains details pertinent to this particular study.

Data for this study originated from all three livestock farmlets of the NWFP and covers five grazing seasons between 2015 and 2019. The final dataset included 1364 lambs and their mother ewes (389 in total) (see Annex at end of thesis). Across the five seasons, lambs were finished at an average of 177 days. Post-slaughter, information on cold carcass weight, carcass quality and current carcass price (obtained from the abattoir) were combined to compute the realised carcass value for each lamb and, as discussed above, employed as an *outcome* variable alongside the slaughter age. In addition, 10 animal-level variables summarised in **Table 5.1** were considered as potential predictors.

### 5.2.3. Case study of the UK sheep sector — methods

Using the dataset described in the previous subsection, the gross information value of each predictor was defined by the potential benefit of employing adaptive management based on the said predictor value, as evaluated through the impact on the two outcome variables that are strongly associated with realised lamb sales and profit (defined above). Specifically, this information value was calculated in four stages **(Figure 5.1)**. Firstly, all lambs in the dataset were ordered according to the predictor value, for example according to their birth weight. Secondly, these lambs were divided into three equal-sized groups according to their rankings, for example top third (high), middle third (med) and bottom third (low) groups according to their birth weight. Thirdly, the mean value for each outcome variable was obtained for each group, for example the average slaughter age of high, med, and low groups. Finally, the difference in this mean value between the high and low groups was calculated and statistically compared via *t*-test. The gross information value thus derived represents the expected economic benefit of an animal ‘upgrading’ from low to high groups according to each predictor, under the assumption that on-farm strategies exist to enable such manipulation.

It is worthwhile noting that the gross information value is exclusive of costs associated with data collection. The decision to use a gross value for the baseline analysis was taken to make the results applicable to a wider spectrum of sheep farms, as substantial variation in geographical conditions, and therefore labour and equipment costs, exists within the UK sheep sector. In other words, the gross value is more independent from the effect of the study site, and thus more directly representative of physiological mechanisms governing sheep performance. Notwithstanding, the implications of considering the cost of data collection will also be briefly investigated in the discussion section.

The analysis outlined above is designed to evaluate the gross information value for each of 10 predictors individually. However, as many predictors are correlated with each other **(Supplementary Tables 5.S1 & 5.S2)**, the benefit of using multiple predictors is not directly cumulative. Furthermore, as these correlations cause multicollinearity, the relative contribution of each predictor variable to the outcome variable cannot be quantified through regression models. To overcome these challenges, the combined gross information value of multiple predictors on carcass value was investigated in the following manner. First, for each predefined number of predictors (1-10), the average ranks of individual lambs across multiple predictors were calculated for every possible combinations of predictors. The number of mathematically possible combinations from a list of 10 variables ranged from 1 (for 10 predictors, $\frac{10!}{1!(10-1)!}$) to 252 (for 5 predictors, $\frac{10!}{5!(10-5)!}$). Using this average ranking, the information value of the relevant combination was estimated in a similar manner as the single predictor case. From these results, the average, maximum and minimum gross information values realised across all possible combinations under each number of predictors was extracted for graphical representation. Finally, in order to appraise the sensitivity of the main findings to an alteration in definition of low performing and high performing groups, the entire process was repeated using two alternative classification rules for lambs, under which the high and low groups were defined from equal halves (top half and bottom half) and equal quarters (top quarter and bottom quarter) according to the predictor value.

All data analyses were conducted using R version 4.0.2 (R Core Team, 2020).

## 5.3. Results

When slaughter age was used as the outcome variable, predictors directly linked to lamb weight had the highest information value. Weaning weight, 8-week weight and 4-week weight showed an average value of 84.9, 75.2 and 64.4 days (to slaughter), respectively **(Table 5.2)**. Using carcass value as the outcome, predictors linked to ewe weight and body condition score (BCS) were more valuable than those linked to lamb weight, with ewe weight and BCS at lambing valued at £3.34 and £2.69, respectively. The discrepancy between the most informative (ewe weight at lambing) and the least informative (ewe weight at weaning) predictors was £2.35, demonstrating a substantial financial benefit to the appropriate selection of metrics.

**Figure 5.2** shows the combined benefits of multiple predictors under the best, average, and worst combinations when different numbers of metrics are used. The gap in information value between the best and worst combinations was found to be pronounced, up to £2.84 under two predictors. This difference gradually reduced as more predictors were added until all 10 predictors were included (thus there is only one ‘combination’). Large differences were also observed between the best and average combinations of predictors, suggesting that predictors which are chosen randomly have substantially less information value than those selected on evidence.

Across all 'best' combinations (using 1-10 predictors), peak benefit of £3.61 was recorded under four predictors: ewe weight at lambing, ewe BCS at lambing, ewe BCS at tupping and lamb weight at birth. The inclusion of additional metrics beyond this point reduced the gross economic benefit regardless of the combination selected. The predictors contributing to high value combinations are identified in **Table 5.3a**, with ewe weight and BCS at lambing both consistently featured in this list. Ewe weight and BCS at weaning, on the other hand, are consistently observed in the lowest ranked combinations, whether used individually or in combination with other predictors **(Table 5.3b)**.

The results of sensitivity analysis suggested that the classification rule to define the high and low groups has a minimal impact on predictor rankings **(Supplementary Tables 5.S3 & 5.S4)**. For the vast majority of cases, optimal combinations identified under the baseline method remained high-ranked under alternative rules **(Supplementary Table 5.S5)**, indicating that the findings reported above are not conditional on the inter-animal distribution intrinsic to the current dataset.

## 5.4. Discussion

### 5.4.1. Importance of ewe measurements

The above results indicated that the bodyweight and BCS of ewes have considerable economic importance as predictors of a farm's performance. When ranked individually, the three most valuable predictors were associated with ewes rather than lambs **(Table 5.2)**. The same tendency was also observed under composite rankings, where multiple predictors were combined to increase the overall information values **(Table 5.3)**. These findings suggest that the impact of ewe health extends beyond pre-weaning lamb growth and affects farm profitability through multiple pathways. Thus, if one is forced to make a choice due to practical constraints, recording of ewe data should be prioritised over lamb data on commercial farms.

Compared to the high information values of ewe weight/BCS at lambing, the predictive power of ewe weight/BCS at weaning, while still present, was found to be somewhat muted. It is well established that ewe condition at lambing is associated with subsequent lamb growth rates, as it represents the energy reserves available for meeting the metabolic needs of lactation (Gibb and Treacher, 1980; Keady and Hanrahan, 2006; Kenyon et al., 2014). Contrarily, the exact purpose of ewe condition measurements at weaning — whether this is recommended to gain insight on the lambs' growth prospect or to identify the ewe's nutritional demand prior to the next tupping — has been rather ambiguous in the KPI literature. The present results suggest that this metric does not predict the current season's lamb performance as accurately as ewe BCS at lambing. This is potentially due to the large variation across ewes, even amongst a single breed, in the amount of body reserves mobilised to meet the energy demand for lactation (Macé et al., 2019).

Although ewe BCS at lambing appears to be most strongly linked to lamb growth and carcass value across all tested predictors, as stated this information is only meaningful if the cost of manipulating ewe BCS is outweighed by the subsequent economic benefit. Supplementing ewes with concentrate feeds during pregnancy is known to increase BCS at lambing (Keady et al., 2009) and, in turn, improve lamb growth (Annett et al., 2013); however, the benefit of using a high volume of concentrate feed for this purpose is unlikely to be large enough to justify the cost (Kerslake et al., 2010) and can also invite a range of sustainability issues (Wilkinson and Lee, 2018). As an alternative strategy, a combined use of high-quality grass silage and concentrate feed, or deferred grazing post-lambing, is likely to be substantially more viable (Keady and Hanrahan, 2009, 2012).

Beyond a single season, lambs from ewes in better conditions finish faster and leave the farm earlier in the season, allowing a lower stocking rate for autumn grazing. This pasture surplus can then be used to improve ewe fertility through improved nutrition pre-mating (Phillips et al., 2014) or as supplemental feed during pregnancy (Keady and Hanrahan, 2012), creating a positive feedback loop across multiple seasons. A reduction in grazing pressure could also provide an environmental and ecological benefit, as grazing sheep at lower densities can increase the provision of ecosystem services, such as enhanced runoff water quality, plant productivity and carbon storage (Austrheim et al., 2016). Alternatively, if less land area is required to produce a similar level of output through a shortened slaughter age, surplus land could be set aside for other purposes without compromising food security. Although much of the land used for sheep grazing in the world is marginal and often unsuitable for cultivation of human-edible crops (Eisler et al., 2014; van Zanten et al., 2016), afforestation of this surplus land would sequester carbon (Duffy et al., 2020) and rewilding of this land would facilitate the restoration of both biodiversity and ecosystem processes (Benayas and Bullock, 2015; Loth and Newton, 2018). Both of these approaches can mitigate the environmental impact of agriculture and at the same time increase farm resilience against future external shocks, especially in relation to the future potential of carbon credits to support agroecological farming (Dominati et al., 2019).

#### 5.4.2. Cost of recording information

While the analyses conducted within this study demonstrated a positive gross economic benefit of recording information on the farm, gathering this information is seldom free of cost. On large commercial farms, labour cost is generally monetised. Even on traditional family farms where labour time is often not considered a tangible financial cost, labour saving can allow time to be devoted to other tasks and thus indirectly contributes to operational profitability (Morgan-Davies et al., 2017b). As already discussed, sheep farms can take a wide variety of enterprise structures and, as such, care should be exercised to apply a particular cost assumption to draw general conclusions about the overall financial implications of on-farm measurements. Nevertheless, to assess the value of information in a holistic manner, the costs of both labour time and any necessary equipment must be considered.

To investigate the potential impact of these burdens on the results reported above, an auxiliary analysis was conducted to estimate the *net* information value of each individual predictor with respect to the resultant carcass value. Three cost scenarios were considered based on financial information from the NWFP: (1) equipment is purchased solely for predictor measurements; (2) equipment is newly purchased but its cost is shared between seasonal operational measurements and predictor measurements; and (3) equipment already exists and therefore recording only incurs labour cost **(Table 5.4)**. As expected, the absolute value of net benefit was highly sensitive to the cost assumption. However, the relative benefit between predictors remained unchanged, indicating that the priority ranking complied from the *gross* information value is robust to the cost assumption adopted **(Table 5.5)**.

When the third assumption was extended to composite rankings from multiple predictors, using six predictors or more resulted in a negative net information value **(Figure 5.3)**. This finding is driven by the combination of cumulative labour cost required to carry out additional measurements and the relatively small incremental gross benefit of using this information, the latter of which stems from a flat shape of the original response curve **(Figure 5.2)**. Between options with positive net information values, a single (non-composite) predictor (ewe weight at lambing) demonstrated the highest net value (£2.86), although the difference between this option and the best combination of two predictors (ewe weight and BCS at lambing, £2.45) was only marginal.

Further research is required, however, to investigate the production environment under which the above result of 'you only need a single metric' is applicable. As a research farm, the NWFP benefits from a higher allowance for labour input than most commercial farms, making good agricultural practices more easily implementable. In conjunction with a flock structure and management strategy which do not fluctuate between years, this contributes to a lower level of volatility in livestock productivity, and as a result less variation in ewe and lamb performance over time. The predictors used in this study therefore are likely to have a higher degree of correlation between them, which reduces the benefit of measuring additional predictors. Thus, on commercial farms that are less regimented and governed by managerial decisions more adaptive than prescriptive, the incremental benefit of using multiple predictors, thereby reducing statistical noise, may be more profound.

### 5.4.3. Applicability in commercial settings

The analytical framework developed in this study provides an objective means to estimate the financial benefit of animal-level performance predictors. Practically speaking, however, the proposed method requires a certain degree of variability in both predictor and outcome variables; homogeneous animals reared under a single system cannot be differentiated. As the dataset used here originates from a research farm composed of three distinct grassland systems (permanent pasture, reseeded grass monoculture and reseeded legume/grass mix: see Chapter 2), the validity of the framework within a single enterprise — the environment more resembling ordinary commercial farms — is worth evaluating. As such, the quantitative analysis described above was repeated separately for the three farmlets.

The results of this analysis were promising. For example, the most informative predictor for isolated use (ewe weight at lambing) was found to be worth £3.22, £3.26, and £3.99 across three systems, largely comparable to the value estimated for the full dataset (£3.34, **Table 5.2**). The best predictor combination for composite use (ewe weight at lambing, ewe BCS at lambing, ewe BCS at tupping and lamb weight at birth) were worth £3.52, £2.48, and £4.41, respectively, slightly fluctuated from the full dataset value (£3.49) but still all successfully ($p < 0.05$) differentiating the performance between the high and low groups as defined by predictor values. Given that the predictor variability *within a single farming system* is likely to be smaller on research farms than on commercial farms, the proposed method thus appears to be also suitable for data obtained outside an experimental environment.

Within individual farming systems, one possible use of the proposed framework is to pool data from multiple enterprises and develop a revised list of industry-recommended KPIs. As each KPI can now be accompanied by the potential economic value of the measurement, such a list may encourage more farmers to make an effort to obtain mid-season metrics to improve their production efficiency. Yet longer-term, the output from the current exercise should ideally become directly transformable to actionable benchmarks (trigger points) tailored for an individual farm. As a case in point, while the reported results clearly demonstrate the importance of maintaining ewe health during late pregnancy, this message on its own does not provide sufficient information to determine the exact timing at which interventions such as emergency supplementary feeding should be initiated.

As a step towards converting KPIs into actionable benchmarks, the relationship between the two highest-value predictors (ewe weight and BCS at lambing) and the carcass value of lambs was further investigated **(Supplementary Tables 5.S6 & 5.S7)**. Rather than defining the high and low groups at a pre-determined proportion (e.g. top third and bottom third), the entire flock was split into two groups at multiple threshold values — in an increment of 1 kg for weight and 0.25 points for BCS. The information value calculated under each threshold value represents the maximum cost of intervention a farm would be willing to pay if animals in the low group are to be 'transferred' to the high group.

With ewe weight at lambing used as the predictor, the largest information value (£3.62) was observed when the threshold was set at 84 kg. However, the animals in the high group only accounted for 15% of the flock under this scenario, meaning that any 'intervention' would have to be applied almost blanketly across the whole farm. In addition to the practical challenges associated with a managerial change at this scale, this strategy is unlikely to prove financially viable, as the cost of intervention would be prohibitively high and the likelihood of successful intervention disproportionally low when performance targets are as ambitious. Ewe BCS at lambing, on the other hand, showed a more balanced split and an achievable target under the maximum information value (£2.40, 51% in the high group when the threshold is set at the BCS score of 3.25), and thus may provide an attractive alternative to bodyweight in this context (Behrendt et al., 2011). Needless to say, full optimisation of intervention strategies would require detailed information on how animals respond to different forms of intervention, which is beyond the scope of the present study. Nevertheless, the proposed framework has two interrelated but separate pathways to facilitate evidence-based livestock farming, one through generic lists of recommended KPIs and another through more tailored decision support for individual farm management.

### 5.4.4. Implications for the UK sheep sector

The results here demonstrated a high degree of variation in information value between different predictors, indicating that predictors selected through quantitative assessment are substantially more likely to have a positive impact on a farm's profitability than those randomly or instinctively chosen. As briefly discussed in Chapter 1, this information is particularly pertinent to the UK sheep sector today, as the country's withdrawal from the European Union is predicted to have a detrimental impact on farm income when European-style direct payments are phased out from 2021 (Patton et al., 2017; Downing et al., 2018). Of all agricultural enterprises, sheep farms are predicted to be the worst affected, with some studies estimating that 70% of farms will be unprofitable once changes are in place (Hubbard et al., 2018). Farms which are unable or unwilling to adapt to the new economic environment are likely to face bankruptcy, and many older farmers are expected to retire (Dwyer, 2018).

The direct payments are to be succeeded by environmental land management schemes, which aim to improve the provision of 'public money for public goods' through environmental enhancement (DEFRA, 2018). As this financial 'support' will only be provided in exchange for tangible provision of ecosystem services, it may lead to further fragmentation of the already stratified sheep sector (Rodriguez-Ledesma et al., 2011). In particular, sheep farms based in hill and upland areas, who have historically been the most reliant on agricultural subsidies (Thompson, 2009), will likely be pushed towards environmental land stewardship and away from sheep production (Angus et al., 2009; Howley et al., 2015), rendering the findings of this study potentially less relevant (Hardaker, 2018; Arnott et al., 2019). Lowland sheep farms have generally been more productive and relatively less reliant on support payments, although in order to remain so in the absence of hill and upland farms, which often provide them with breeding units (Rodriguez-Ledesma et al., 2011), these farms will also need to make substantial improvements in profitability. These changes are likely to resemble those undergone by sheep farms in New Zealand following their agricultural transition in the late 1980s, which resulted in an increase in average farm size, reduction in labour input, identification of enterprise components contributing least to farm income and, ultimately, improvement in productivity (Morrison Paul et al., 2000; Johnsen, 2004; Gouin, 2006). Judging by this example, enhanced profitability is unlikely to be made without a detailed and accurate understanding of production processes and their contributions to the overall performance of the enterprise. The uptake of a more informed KPI decision support system, therefore, seems critical for UK sheep farms' survival into the future.

### 5.4.5. General discussion

The above analysis of UK sheep farms has provided a case exemplar of how the value of information can be defined and subsequently used to select the most useful predictors, or 'key' performance indicators, of which measurements should be prioritised. As stated above, the proposed framework is directly extendable to other livestock species and possibly beyond. Nonetheless, to effectively tailor the developed methodology to different farming enterprises, appropriate predictors, outcomes, and cost assumptions must all be carefully considered.

For example, sheep in the UK are predominantly pasture-fed and undergo a yearly production cycle with a single crop of lambs that are valued according to their carcass weight and carcass quality (Jones et al., 2004). Under this enterprise structure, the carcass value is arguably the most suitable outcome against which to assess the information value of predictors, as farm revenue is almost exclusively derived from this metric. However, for sectors operating under a less seasonal environment, for example indoor dairy and laying hen systems, outcome measures corresponding to the animal's lifetime contribution to the enterprise may not be the most appropriate predictors, as they offer less opportunities for adaptive management (Ahmad and Roland, 2003; Bell and Wilson, 2018). In addition, the impact of measurement costs on the overall information value is likely to be smaller under these systems, especially if additional precision agriculture techniques are already in place to reduce labour requirements for information gathering (Wathes et al., 2008; Morgan-Davies et al., 2017a). Thus, the exact implementation process of the KPI selection framework will vary depending on the production system. Regardless, a holistic approach involving a wide range of factors contributing to farm profitability will remain essential to ensure the optimal system-wide information value.

Finally, while the role of animal-level KPIs in the improvement of overall farm efficiency has been clearly demonstrated in the present study, I acknowledge the complexity of livestock farming businesses beyond animal husbandry. Even the simplest form of farm enterprises face numerous non-livestock decisions on a daily basis (Bohan et al., 2016), to ensure, amongst others, soil health (Takahashi et al., 2018), pasture growth (Behrendt et al., 2016; Earle et al., 2018), and appropriate procurement and sales channels (Bensemann and Shadbolt, 2015). Each of these decisions can potentially be improved through additional information, of which collection and collation require labour time that competes against what is dedicated on animal husbandry. To this end, an extended framework to optimise the enterprise-wide information value of both livestock and non-livestock measurements will likely increase the value of KPIs even further, as discussed in the next and final chapter.

**Table 5.1.** Key performance indicators currently in common usage

| Indicator | Predictor | Outcome | Descriptor | Level applied | Current justification |
|---|---|---|---|---|---|
| Birth weight | X | | | Lamb | (Juengel et al., 2018) |
| Four-week weight | X | | | Lamb | (Wright, 2015) |
| Eight-week weight | X | | | Lamb | (Wright, 2015) |
| Weaning weight | X | | | Lamb | (EBLEX, 2014a) |
| Average daily liveweight gain | X | | | Lamb | (Gascoigne and Lovatt, 2015) |
| Slaughter age | | X | | Lamb | (Kerr, 2000) |
| Carcase conformation | | X | | Lamb | (Fisher and Heal, 2001) |
| Fat class | | X | | Lamb | (Fisher and Heal, 2001) |
| Kill-out percentage | | X | | Lamb | (Matthews and Ford, 2012) |
| Cold carcase weight | | X | | Lamb | (Stanford et al., 1998) |
| Body condition score | X | | | Ewe | (Kenyon et al., 2014) |
| Change in BCS | X | | | Ewe | (Kenyon et al., 2014) |
| Weight | X | | | Ewe | (Brown et al., 2015) |
| Weight change | X | | | Ewe | (Brown et al., 2015) |
| % lambs failing to reach 85% target weight | X | | | Farm | (Wright, 2018) |
| Ewe to Ram ratio | | | X | Farm | (EBLEX, 2008) |
| Scanning percentage | X | | | Farm | (Earle et al., 2016) |
| % empty ewes at scanning | X | | | Farm | (EBLEX, 2008) |
| Lambing percentage | X | | | Farm | (Morris, 2009) |
| Lambs alive after 48hrs | X | | | Farm | (AHDB, 2015) |
| Lambs weaned | X | | | Farm | (Bohan et al., 2018) |
| Lambs reared | | X | | Farm | (AHDB, 2018) |
| Lamb losses from scanning to birth | X | | | Farm | (EBLEX, 2014a) |
| 90 day lamb weight per ewe to ram | X | | | Farm | (AHDB, 2018) |
| Weight of lamb reared per ewe to ram | | X | | Farm | (EBLEX, 2014b) |
| Percentage of empty ewes | X | | | Farm | (EBLEX, 2008) |
| Ewe mortality | X | | | Farm | (EBLEX, 2014b) |
| Percentage of ewes culled | | | X | Farm | (EBLEX, 2008) |
| Flock replacement rate | | | X | Farm | (EBLEX, 2014b) |

**Table 5.2.** Gross information values of individual predictors

| Predictors | Gross benefit | | | |
|---|---|---|---|---|
| | Slaughter age (days) | | Carcass value | |
| Birth weight | -39.89 (-45.77, -34.02) | *** | £1.80 (0.83, 2.77) | *** |
| Four-week weight | -64.41 (-69.55, -59.26) | *** | £1.50 (0.52, 2.48) | ** |
| Eight-week weight | -75.15 (-79.86, -70.45) | *** | £1.52 (0.53, 2.51) | ** |
| Weaning weight | -84.87 (-89.27, -80.46) | *** | £2.20 (1.19, 3.22) | *** |
| Ewe BCS at lamb | -16.37 (-22.52, -10.23) | *** | £2.69 (1.74, 3.63) | *** |
| Ewe BCS at wean | -18.40 (-24.63, -12.17) | *** | £0.99 (0.03, 1.96) | * |
| Ewe BCS at tupping | 3.97 (-2.19, 10.14) | | £1.32 (0.37, 2.27) | ** |
| Ewe weight at lamb | -17.44 (-23.83, -11.04) | *** | £3.34 (2.36, 4.31) | *** |
| Ewe weight at wean | -23.16 (-29.17, -17.14) | *** | £0.99 (0.05, 1.92) | * |
| Ewe weight at tupping | -9.72 (-15.98, -3.46) | ** | £2.28 (1.29, 3.26) | *** |

Darker shades indicate higher information values.
Confidence intervals shown in parentheses.
Significance codes: *** $p < 0.001$; ** $p < 0.01$; *$p < 0.05$

**Table 5.3.** Predictors with highest and lowest values when used in combination with other predictors

(a) metric combinations with highest benefit

Number of metrics used; Ranking of combination

| | One | | | Two | | | Three | | | Four | | | Five | | | Six | | | Seven | | | Eight | | | Nine | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd |
| Birth weight | | | | | | ✓ | | | | ✓ | | | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | |
| Four-week weight | | | | | | | | ✓ | | | | | ✓ | | | | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Eight-week weight | | | | | | | ✓ | | | | | | | | | ✓ | | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | ✓ |
| Weaning weight | | | | | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Ewe BCS at lambing | | ✓ | | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at weaning | | | | | | | | | | | | | | | | | | | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at tupping | | | | | | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at lambing | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at weaning | | | | | | | | | | | | | | | | | | | | | | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Ewe weight at tupping | | | ✓ | | | | | | ✓ | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

(b) metric combinations with lowest benefit

Number of metrics used; Ranking of combination

| | One | | | Two | | | Three | | | Four | | | Five | | | Six | | | Seven | | | Eight | | | Nine | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd |
| Birth weight | | | | | | | | | | | | ✓ | | ✓ | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Four-week weight | | | | | | | | | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Eight-week weight | | | | | ✓ | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Weaning weight | | | | | | | | | | | | ✓ | | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at lambing | | | | | | | | | | | | | | | | | | | ✓ | | | ✓ | | | ✓ | | ✓ |
| Ewe BCS at weaning | | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at tupping | | | ✓ | | | ✓ | | ✓ | | | ✓ | | ✓ | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Ewe weight at lambing | | | | | | | | | | | | | | | | | | | | | | | ✓ | ✓ | | ✓ | ✓ |
| Ewe weight at weaning | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at tupping | | | | | | | | | | | | | | | | | | | | | ✓ | | | ✓ | ✓ | ✓ | |

**Table 5.4.** Cost scenarios used to estimate net information values

**Scenario 1. Equipment is purchased solely for predictor measurements**

| Measurement | Equipment cost per lamb† | Labour cost per lamb‡ | Total cost per lamb |
|---|---|---|---|
| Ewe weight* | £1.37 | £0.30 | £0.89 |
| Ewe BCS* | £1.37 | £0.35 | £0.91 |
| Lamb weight | £0.82 | £0.30 | £1.12 |

**Scenario 2. Equipment is newly purchased but its cost is shared with operational measurements (once a year)**

| Measurement | Equipment cost per lamb† | Labour cost per lamb‡ | Total cost per lamb |
|---|---|---|---|
| Ewe weight* | £0.51 | £0.30 | £0.43 |
| Ewe BCS* | £0.51 | £0.35 | £0.46 |
| Lamb weight | £0.41 | £0.30 | £0.71 |

**Scenario 3. Equipment already exists and therefore recording only incurs labour cost**

| Measurement | Equipment cost per lamb† | Labour cost per lamb‡ | Total cost per lamb |
|---|---|---|---|
| Ewe weight* | - | £0.30 | £0.16 |
| Ewe BCS* | - | £0.35 | £0.19 |
| Lamb weight | - | £0.30 | £0.30 |

* Corrected for the average litter size (1.88).

† Based on the following assumptions about capital costs and life cycles — SRS2 stick reader: £620.17 over 5 years. EziWeigh7i weighing head: £815.08 over 10 years. Border Software weigh crate: £2,724 over 10 years. Handling system: £5395 over 30 years.

‡ Based on the following assumptions about labour requirements and wage rate — Weighing: 0.9 minutes per animal. BCS: 1.05 minutes per animal. Wage rate: £20 per hour or 0.33p per minute (encompassing two workers).

**Table 5.5.** Net information values of individual predictors based on realised carcass value

| Predictors | Gross benefit | Net benefit | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Birth weight | £1.80 | -£1.57 | -£0.33 | £0.90 |
| Four-week weight | £1.50 | -£1.86 | -£0.63 | £0.61 |
| Eight-week weight | £1.52 | -£1.85 | -£0.62 | £0.62 |
| Weaning weight | £2.20 | -£1.16 | £0.07 | £1.30 |
| Ewe BCS at lamb | £2.69 | -£0.06 | £1.31 | £2.13 |
| Ewe BCS at wean | £0.99 | -£1.75 | -£0.39 | £0.43 |
| Ewe BCS at tupping | £1.32 | -£1.42 | -£0.05 | £0.77 |
| Ewe weight at lamb | £3.34 | £0.67 | £2.04 | £2.86 |
| Ewe weight at wean | £0.99 | -£1.68 | -£0.31 | £0.51 |
| Ewe weight at tupping | £2.28 | -£0.39 | £0.98 | £1.80 |

Darker shades indicate higher information values.

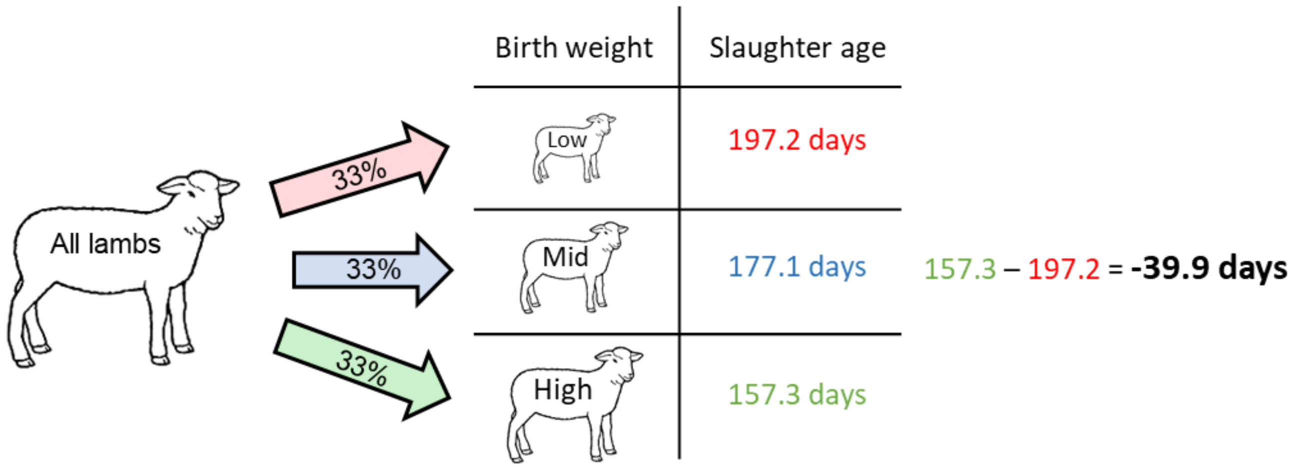


**Figure 5.1.** Proposed method to estimate the gross information value of a predictor. It is computed as the difference in end-of-season performance outcome (slaughter age in this example) between top (high) and bottom (low) groups, as defined mid-season according to the relevant predictor value (birth weight in this example). Top third and bottom third animals were allocated to 'high' and 'low' groups, respectively, for the baseline analysis. However, main results were insensitive to changes in how these two groups were defined. Produced by the authors using Microsoft PowerPoint.

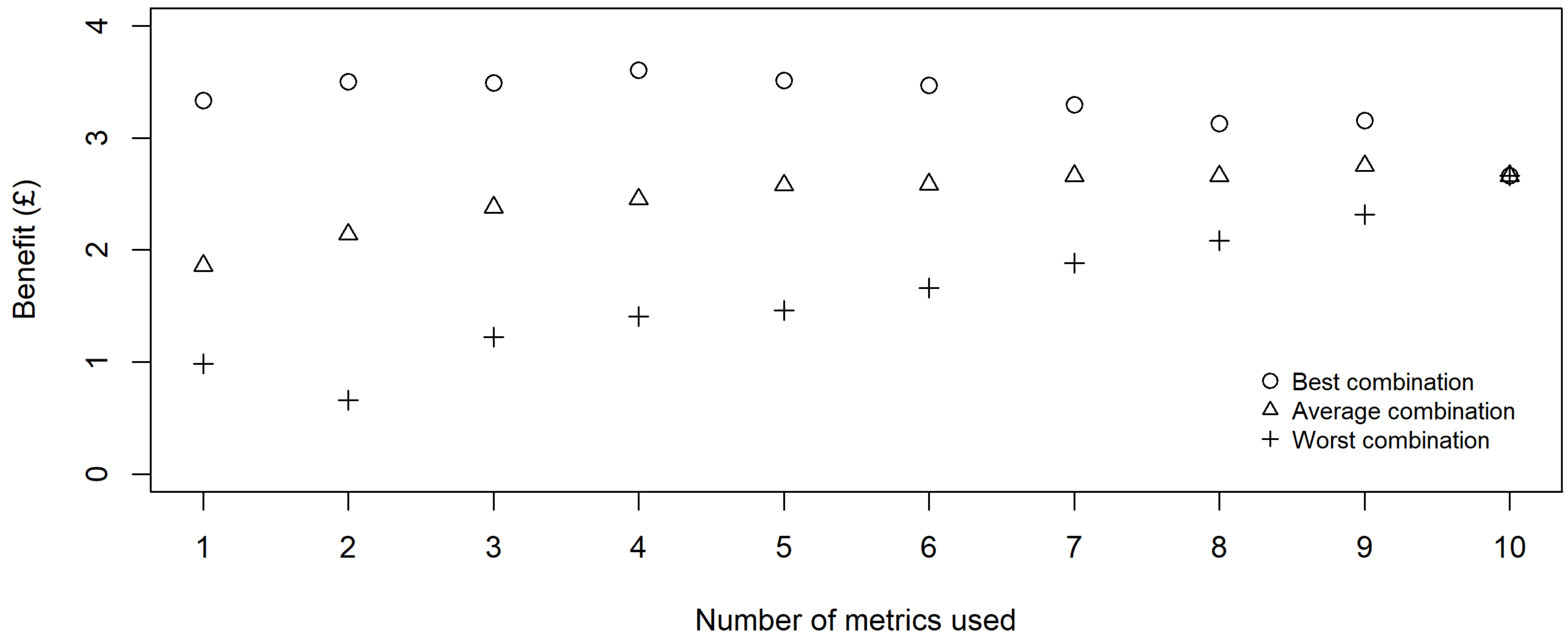


**Figure 5.2.** Combined gross information value of multiple predictors. A considerable variability in information value is observed even when the same number of predictors is used, demonstrating the importance of selecting key performance indicators based on quantitative evidence.

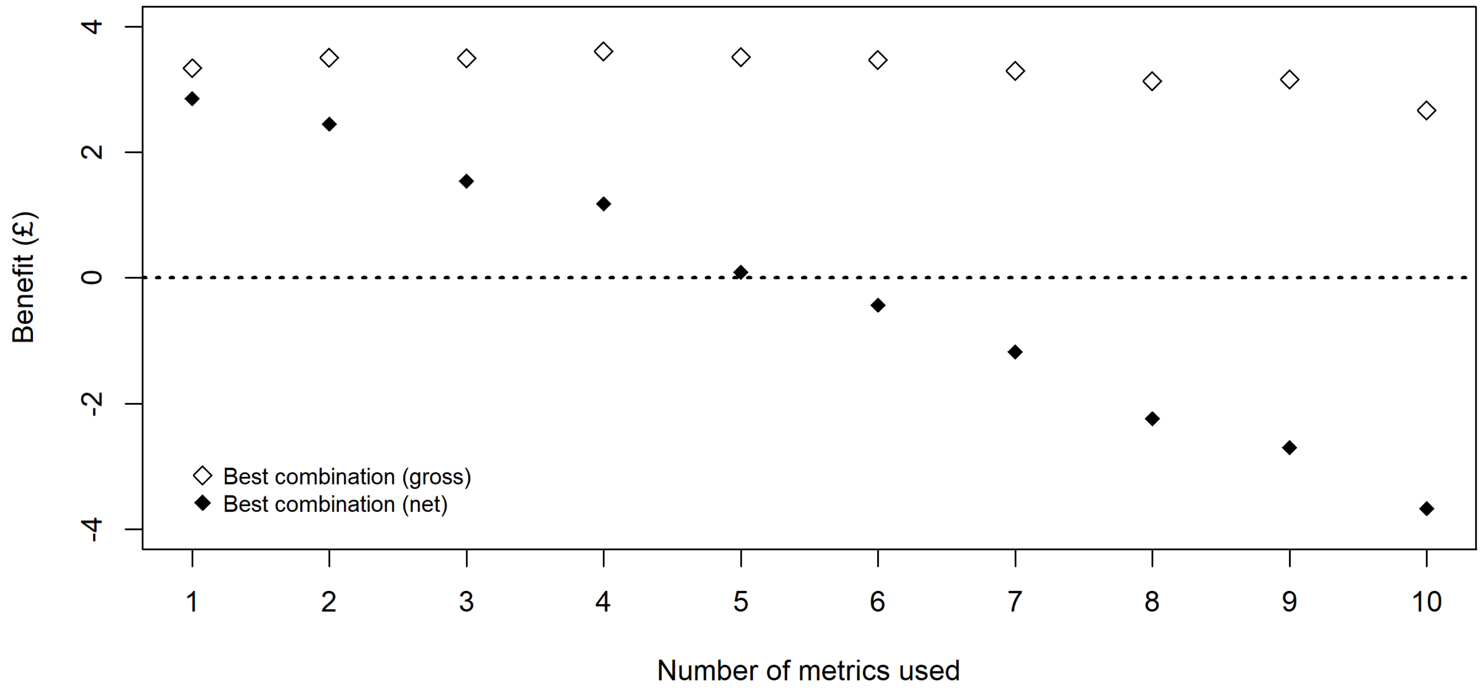


**Figure 5.3.** Gross and net information values of multiple predictors. Due to the flat shape of the gross curve, the net value linearly decreases as additional measurement costs are incurred.

## Appendix to Chapter 5.

**Table 5.S1.** Correlation matrix between performance predictors

| | BW | A4W | A8W | WW | BAL | BAW | BAT | WAL | WAW | WAT |
|---|---|---|---|---|---|---|---|---|---|---|
| BW | 1 | | | | | | | | | |
| A4W | 0.696 | 1 | | | | | | | | |
| A8W | 0.599 | 0.880 | 1 | | | | | | | |
| WW | 0.476 | 0.760 | 0.853 | 1 | | | | | | |
| BAL | 0.106 | 0.271 | 0.225 | 0.192 | 1 | | | | | |
| BAW | 0.057 | 0.148 | 0.170 | 0.194 | 0.428 | 1 | | | | |
| BAT | -0.083 | -0.123 | -0.136 | -0.080 | 0.189 | 0.252 | 1 | | | |
| WAL | 0.196 | 0.306 | 0.251 | 0.242 | 0.589 | 0.247 | 0.017 | 1 | | |
| WAW | 0.151 | 0.193 | 0.176 | 0.249 | 0.317 | 0.594 | 0.137 | 0.639 | 1 | |
| WAT | 0.125 | 0.143 | 0.112 | 0.125 | 0.247 | 0.180 | 0.219 | 0.689 | 0.641 | 1 |

BW=lamb birth weight; A4W=adjusted lamb weight at four weeks; A8W=adjusted lamb weight at eight weeks; WW=lamb weight at weaning; BAL=ewe's body condition score at lambing; BAW=ewe's body condition score at weaning; BAT=ewe's body condition score at tupping; WAL=ewe's weight at lambing; WAW=ewe's weight at weaning; WAT=ewe's weight at tupping.

**Table 5.S2.** *P*-values for correlations between performance predictors

| | BW | A4W | A8W | WW | BAL | BAW | BAT | WAL | WAW | WAT |
|---|---|---|---|---|---|---|---|---|---|---|
| BW | 0 | | | | | | | | | |
| A4W | <0.001 | 0 | | | | | | | | |
| A8W | <0.001 | <0.001 | 0 | | | | | | | |
| WW | <0.001 | <0.001 | <0.001 | 0 | | | | | | |
| BAL | <0.001 | <0.001 | <0.001 | <0.001 | 0 | | | | | |
| BAW | 0.073 | <0.001 | <0.001 | <0.001 | <0.001 | 0 | | | | |
| BAT | 0.009 | <0.001 | <0.001 | 0.010 | <0.001 | <0.001 | 0 | | | |
| WAL | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.528 | 0 | | |
| WAW | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0 | |
| WAT | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0 |

BW=lamb birth weight; A4W=adjusted lamb weight at four weeks; A8W=adjusted lamb weight at eight weeks; WW=lamb weight at weaning; BAL=ewe's body condition score at lambing; BAW=ewe's body condition score at weaning; BAT=ewe's body condition score at tupping; WAL=ewe's weight at lambing; WAW=ewe's weight at weaning; WAT=ewe's weight at tupping.

All values have been adjusted for multiple tests using the Holm method.

**Table 5.S3.** Predictors with high and low information values when used in combination with other predictors — under the quartile rule (25%/50%/ 25%) to define top and bottom groups

(a) metric combinations with highest benefit

| | Number of metrics used | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | One | | | Two | | | Three | | | Four | | | Five | | | Six | | | Seven | | | Eight | | | Nine | | |
| | Ranking of combination | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd |
| Birth weight | | | | | | | | | ✓ | | | | | ✓ | | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Four-week weight | | | | | | | | ✓ | | | | ✓ | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Eight-week weight | | | | | | | | | | ✓ | | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | | | ✓ | ✓ |
| Weaning weight | | | | | ✓ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at lambing | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at weaning | | | | | | | | | | | | | | | | | ✓ | | | ✓ | | | | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at tupping | | | | | | | | | | | | | | ✓ | | | | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at lambing | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at weaning | | | | | | | | | | | | | | | | | | ✓ | | | | ✓ | | | ✓ | ✓ | ✓ |
| Ewe weight at tupping | | ✓ | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

(b) metric combinations with lowest benefit

| | Number of metrics used | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | One | | | Two | | | Three | | | Four | | | Five | | | Six | | | Seven | | | Eight | | | Nine | | |
| | Ranking of combination | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd |
| Birth weight | | | | | | | | | | | ✓ | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Four-week weight | | | | | | ✓ | | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Eight-week weight | | | | | | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Weaning weight | | | | | | | | | | | | | ✓ | | | | ✓ | ✓ | | | | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Ewe BCS at lambing | | | | | | | | | | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Ewe BCS at weaning | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at tupping | | | ✓ | | ✓ | | ✓ | | ✓ | | | ✓ | | ✓ | | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at lambing | | | | | | | | | | | | | | | | ✓ | | | | | | | | ✓ | ✓ | | ✓ |
| Ewe weight at weaning | ✓ | | | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at tupping | | | | | | | | | | | | | | | ✓ | | | | ✓ | ✓ | | | ✓ | | | ✓ | ✓ |

**Table 5.S4.** Predictors with high and low information values when used in combination with other predictors — under the equal half rule (50%/ 50%) to define top and bottom groups

(a) metric combinations with highest benefit

| | Number of metrics used | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | One | | | Two | | | Three | | | Four | | | Five | | | Six | | | Seven | | | Eight | | | Nine | | |
| | Ranking of combination | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd |
| Birth weight | | | | | ✓ | | | ✓ | | | | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Four-week weight | | | | | | ✓ | | | | | | | | | | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Eight-week weight | | | | | | | ✓ | | | | ✓ | | | | ✓ | | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Weaning weight | | | ✓ | | | | | | | ✓ | | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at lambing | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at weaning | | | | | | | | | | | | | | | ✓ | | ✓ | | ✓ | | | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Ewe BCS at tupping | | | | | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at lambing | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at weaning | | | | | | | | | | | | | | | | | | | | | | | | | | ✓ | ✓ |
| Ewe weight at tupping | | | | ✓ | | | | | | | | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |

(b) metric combinations with lowest benefit

| | Number of metrics used | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | One | | | Two | | | Three | | | Four | | | Five | | | Six | | | Seven | | | Eight | | | Nine | | |
| | Ranking of combination | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd | 1st | 2nd | 3rd |
| Birth weight | | | | | | | | | | | | | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Four-week weight | | | | | | | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Eight-week weight | | ✓ | | ✓ | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Weaning weight | | | | | | | ✓ | | | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at lambing | | | | | | | | | | | | | | | | | ✓ | | ✓ | | | ✓ | | | ✓ | | ✓ |
| Ewe BCS at weaning | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe BCS at tupping | | | | | | | | | | | | | | | | | | ✓ | | | ✓ | | ✓ | ✓ | | ✓ | ✓ |
| Ewe weight at lambing | | | | | | | | | | | | | | | | | | | | | | | | ✓ | ✓ | ✓ | |
| Ewe weight at weaning | | | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Ewe weight at tupping | | | | | | | | | | | | | | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

**Table 5.S5.** Rankings of high-value and low-value predictor combinations under alternative definitions of top and bottom groups

(a) metric combinations with highest benefit under baseline analysis

| | One | | | Two | | | Three | | | Four | | | Five | | | Six | | | Seven | | | Eight | | | Nine | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Baseline (thirds) | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Quarters | 1 | 3 | 2 | 1 | 2 | 5 | 11 | 4 | 10 | 23 | 24 | 13 | 25 | 38 | 5 | 12 | 19 | 15 | 17 | 37 | 22 | 19 | 10 | 25 | 7 | 1 | 3 |
| Halves | 2 | 1 | 4 | 6 | 7 | 2 | 1 | 6 | 5 | 13 | 57 | 1 | 21 | 13 | 5 | 3 | 4 | 5 | 70 | 8 | 3 | 14 | 16 | 4 | 7 | 6 | 5 |
| Combinations* | | 10 | | | 45 | | | 120 | | | 210 | | | 252 | | | 210 | | | 120 | | | 45 | | | 10 | |

(b) metric combinations with lowest benefit under baseline analysis

| | One | | | Two | | | Three | | | Four | | | Five | | | Six | | | Seven | | | Eight | | | Nine | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Baseline (thirds) | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Quarters | 1 | 2 | 3 | 1 | 15 | 2 | 6 | 1 | 2 | 1 | 3 | 50 | 2 | 8 | 5 | 14 | 2 | 6 | 7 | 4 | 13 | 1 | 7 | 16 | 2 | 3 | 1 |
| Halves | 3 | 1 | 4 | 2 | 3 | 7 | 2 | 18 | 8 | 3 | 20 | 25 | 45 | 6 | 35 | 1 | 17 | 33 | 7 | 8 | 41 | 13 | 28 | 5 | 3 | 2 | 8 |
| Combinations* | | 10 | | | 45 | | | 120 | | | 210 | | | 252 | | | 210 | | | 120 | | | 45 | | | 10 | |

* Unique patterns available under each number of metrics

**Table 5.S6.** Actionable benchmarks determined by ewe's weight at lambing

| Top group, >= 'X' kg | Carcass value of top group | Carcass value of bottom group | Difference | Proportion requiring intervention |
|---|---|---|---|---|
| 86 | £77.22 | £73.98 | £3.23 | 90% |
| 85 | £77.17 | £73.90 | £3.27 | 87% |
| 84 | £77.39 | £73.77 | £3.62 | 85% |
| 83 | £77.06 | £73.76 | £3.30 | 83% |
| 82 | £76.99 | £73.69 | £3.30 | 81% |
| 81 | £76.94 | £73.58 | £3.36 | 78% |
| 80 | £76.81 | £73.52 | £3.29 | 76% |
| 79 | £76.93 | £73.35 | £3.59 | 73% |
| 78 | £76.75 | £73.31 | £3.44 | 71% |
| 77 | £76.58 | £73.25 | £3.33 | 68% |
| 76 | £76.02 | £73.35 | £2.67 | 64% |
| 75 | £75.84 | £73.32 | £2.52 | 60% |
| 74 | £75.68 | £73.31 | £2.37 | 58% |
| 73 | £75.56 | £73.18 | £2.39 | 52% |
| 72 | £75.33 | £73.19 | £2.14 | 48% |
| 71 | £75.22 | £73.17 | £2.05 | 44% |
| 70 | £75.06 | £73.22 | £1.85 | 40% |
| 69 | £74.96 | £73.05 | £1.92 | 34% |
| 68 | £75.00 | £72.72 | £2.27 | 30% |
| 67 | £74.87 | £72.74 | £2.13 | 26% |
| 66 | £74.81 | £72.55 | £2.26 | 22% |
| 65 | £74.71 | £72.59 | £2.12 | 19% |
| 64 | £74.59 | £72.84 | £1.75 | 16% |
| 63 | £74.54 | £72.82 | £1.73 | 13% |
| 62 | £74.54 | £72.54 | £2.00 | 11% |
| 61 | £74.50 | £72.44 | £2.06 | 9% |

**Table 5.S7.** Actionable benchmarks determined by ewe's BCS at lambing

| Top group, >= 'X' BCS | Carcass value of top group | Carcass value of bottom group | Difference | Proportion requiring intervention |
|---|---|---|---|---|
| 4 | £76.11 | £74.23 | £1.88 | 95% |
| 3.75 | £76.42 | £74.04 | £2.37 | 88% |
| 3.5 | £75.77 | £73.59 | £2.18 | 67% |
| 3.25 | £75.53 | £73.13 | £2.40 | 51% |
| 3 | £74.69 | £73.25 | £1.44 | 26% |
| 2.75 | £74.59 | £73.28 | £1.31 | 21% |
| 2.5 | £74.35 | £73.99 | £0.36 | 10% |
| 2.25 | £74.29 | £74.69 | -£0.40 | 6% |
| 2 | £74.33 | £72.07 | £2.27 | 1% |

# Chapter 6. Conclusion

The findings reported within this thesis provide novel contributions to the field of agricultural science as well as practical information to support sheep producer management decisions. Collectively, the three substantial chapters demonstrate the value of Key Performance Indicators (KPIs) to support management decisions, and above all the merit of selecting appropriate KPIs based on quantitative evidence. As discussed in Chapter 1, the research questions of these studies were selected to examine the three elements which dictate the value of information: accuracy, impact, and application. Accuracy was primarily investigated in Chapter 3, which provided evidence to support a RPM pasture walk protocol that was sufficiently accurate but required 51.2% less labour time than the conventional method and could thus encourage the uptake of this technique within the sector. Impact was primarily investigated in Chapter 4, which identified a link between a lamb’s early life liveweight and subsequent carcass value, therefore highlighting a key point of intervention which could be used to drive improvements in whole-farm profitability. Finally, application was primarily investigated in Chapter 5, which developed a framework for identifying the value of recording on-farm information under various combinations and frequencies and then defining actionable benchmarks for interventions.

Although the KPI ranking framework developed in Chapter 5 was applied to 10 animal-level metrics therein, this method was designed, and is intended, to be extendable to other elements of farm performance. Within each individual farm there are multiple aspects of the enterprise which can be measured in order to support management decisions, for example measurements associated with soil management (e.g. application of fertilisers), pasture management (e.g. timing of silage cut), grazing management (e.g. animal rotation), and business management (e.g. investment in infrastructure). However, each farmer has a finite amount of time and resources available and therefore, ultimately, the value of information collected on the farm must be maximised across all elements of farm management. In this regard it is worth noting that, while pasture metrics and livestock metrics were studied separately within this thesis, the framework presented here is readily extendable to compare the relative value associated with recording each type of information, including that originating from other livestock and arable enterprises within the farm, and thus provide a whole-business approach to assessing how information recording should be prioritised.

The main limitation associated with the results reported within this thesis regards the findings being generated from a single study site, namely the North Wyke Farm Platform (NWFP), and thus do not account for inter-farm variation. As discussed in Section 1.4 there is substantial variation present within the UK sheep sector, both in terms of the biophysical properties of the farm (e.g. climate, soil type, topography, rainfall) as well as the breed and farming practices therein. As already acknowledged within the discussion section of each chapter, subsets of quantitative findings are conditional on these locational and farming system factors. The methodologies, however, will still be applicable even under different conditions, enabling the identification of valuable metrics to meet the requirements of individual farming enterprises.

This thesis has demonstrated the value of making farm management decisions based on evidence and presented a method for identifying which aspects of a farming enterprise should be monitored in order to drive tangible change. It is hoped that the findings presented here will provide sheep producers with the means to increase the efficiency of their farming enterprise, and thus go some way to improving the overall economic sustainability of the UK sheep sector.

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# Annex

## Data to identify key drivers of animal growth and carcass quality for temperate lowland sheep production systems

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**Abstract:** With the growing demand for animal-sourced foods and a serious concern over climate impacts associated with livestock farming, the sheep industry worldwide faces the formidable challenge of increasing the overall product supply while improving its resource use efficiency. As an evidence base for research to identify key drivers behind animal growth and carcass quality, longitudinal matched data of 769 ewes and 3214 lambs were collected at the North Wyke Farm Platform, a farm-scale grazing trial in Devon, UK, between 2011 and 2019. A subset of these data was subsequently analysed in a study to assess the feasibility of using a lamb's early-life liveweight as a predictor of carcass quality [1]. The data also have the potential to offer insight into key performance indicators (KPIs) for the sheep industry, or what variables farmers should measure and target to increase profitability.

**Keywords:** farm management, grazing livestock, liveweight, condition score, conformation score, fat class, lamb, ewe

**Specifications table**

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|---|---|
| **Subject** | Agricultural and Biological Sciences |
| **Specific subject area** | Livestock science |
| **Type of data** | Table |
| **How data were acquired** | On a research farm |
| **Data format** | Raw |
| **Parameters for data collection** | A research farm operating under a representative production environment for temperate lowland regions |
| **Description of data collection** | Body condition of ewes and growth of lambs were both directly measured on the farm. Information on carcass quality was obtained from the abattoir following the slaughter of lambs. |
| **Data source location** | Okehampton, Devon, UK (50°46’10”N, 3°54’05”W) |

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| **Data accessibility** | Repository: Mendeley Data<br>DOI: 10.17632/xy3ndcy8jd.1 (embargoed)<br><br>For peer-review:<br>https://data.mendeley.com/datasets/xy3ndcy8jd/draft?a=3c43312b-6acb-47e1-bb3d-e953d0e3d0ae |
| **Related research article** | A.G. Jones, T. Takahashi, H. Fleming, B.A. Griffith, P. Harris, M.R.F. Lee, Using a lamb's early-life liveweight as a predictor of carcass quality, Animal (2020). https://doi.org/10.1016/j.animal.2020.100018. |

**Value of the data**

- Longitudinal matched data of ewes and lambs enable farming system-scale research to improve resource use efficiency
- Such research will simultaneously benefit the farming community with enhanced profitability and broader society with reduced environmental impacts
- The data can also offer insight into key performance indicators (KPIs) for the sheep industry: what variables farmers should measure and target

## 1. Data description

With the growing demand for animal-sourced foods and a serious concern over climate impacts associated with livestock farming, the sheep industry worldwide faces the formidable challenge of increasing the overall product supply while improving its operational and environmental efficiencies [2-3]. The data presented here were collected from the North Wyke Farm Platform (NWFP) [4], a farm-scale grazing trial in Devon, UK, to assist identification of key drivers behind animal growth and carcass quality within the context of temperate lowland sheep production systems. The data encompass 3214 lambs and their mothers (769 ewes) that belonged to the NWFP over a 9-year period between 2011 and 2019.

All data are publicly available from a data repository [5]. The data take a 'rectangular' format with a lamb as the unit of observation, with corresponding ewe information appended to each lamb. This means that an identical set of ewe information appears twice for twin lambs. The following variables are included in the data for each lamb:

- animal ID
- year of production
- sward management (see Section 2)
- date of birth
- date of slaughter
- litter size

- liveweight: date and value
- cold carcass weight
- conformation score
- fat class
- carcass price
- mother’s ID
- mother’s liveweight: date and value
- mother’s condition score: date and value

As a case exemplar to demonstrate the value of the data, a subset was subsequently analysed in a study to assess the feasibility of using a lamb's early-life liveweight as a predictor of carcass quality [1].

## 2. Experimental design, materials, and methods

The NWFP (50°46’10”N, 3°54’05”W) consists of three self-contained grazing livestock enterprises (21 ha each), which operate under different sward management strategies of reseeded grass monoculture, reseeded legume/grass mix and no reseeding (permanent pasture) [4]. The NWFP’s overall design philosophy [6], environmental appraisal [7] and cattle operation [8] have previously been discussed as part of separate studies.

The NWFP’s sheep operation is also detailed elsewhere [9]. Briefly, lambs are produced by a mixed age flock of Suffolk x Mule ewes, mated to terminal sires in October and November each year. Ewes are housed from December, give births in March and April, and turn out to pasture with lambs at 72 hours post-lambing. With a lambing rate of 1.83 lambs are reared as either singles or twins, with one of the triplet-born lambs either cross-fostered onto a single-rearing ewe or artificially reared with milk replacer. In order to minimise the statistical confoundment attributable to the use of milk replacer, the latter group is immediately excluded from the trial. Lambs are weaned at 13 weeks of age and finished at ~45kg, typically around October.

The liveweight of lambs was recorded at birth, four weeks, eight weeks, 13 weeks (weaning) and every two weeks thereafter until finishing. For four-week and eight-week weights that are particularly time-sensitive, a linear adjustment was made to estimate the corresponding weight (when measurements were not taken on the exact day) to ensure inter-animal comparability. Cold carcass weight, conformation score, fat class and carcass price for each lamb were obtained from the abattoir following the slaughter. For ewes, the liveweight and condition score [10] were recorded at tupping, lambing, and weaning. Both lambs and ewes were weighed individually on a weigh crate. Condition scores for ewes were manually assessed by a trained operator.

**Ethics statement**

All animal data used in this study were collected as part of standard farming practices. As such, no part of this research was subject to approval of an ethics committee.

**Acknowledgments**

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**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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