

Improving the heifer rearing efficiency of fully-housed dairy systems in the UK

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Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy (PhD)

January 2023

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For my parents

Declaration

I hereby declare that this thesis is my own and the work herein has not been submitted for any other degree or award. Additional sources of information and assistance that were given to me during the preparation of this thesis have been acknowledged.

Lucy Holly Ross

Acknowledgements

I would like to express my gratitude to my supervisors, Professor Phil Garnsworthy and Assistant Professor Jean Margerison.

Phil, thank you for your relentless support, patience, and encouragement. I really would never have completed my PhD without your guidance, and I will forever be in awe of your expertise and passion for dairy cows.

Jean, thank you for building my confidence as a Nottingham undergraduate and encouraging me to apply for this PhD. You have taught me to never stop advocating for myself and women in agriculture and science.

My sincere appreciation goes to the dairy research team at the University of Nottingham whose patience and hard work have contributed to the collection of my PhD data.

To the technicians, ***Neil Saunders,*** and ***Jen Hankin,*** I appreciate all the time and detail you put into conducting farm trials at UoN. To the students, ***Kirsty Farnan, Sophia Lewin*** and ***Gemma Day,*** your positivity and teamwork made my early starts and long hours easier and cheerier. Also, to ***Leigh Silvester,*** for supporting all my IT needs; there were a few! Lastly, I would like to extend my thanks to the farm staff at the dairy centre, particularly ***Nacia Bonnick*** and ***Emma Gaynor***. I know how committed you were to every calf.

To all my friends at UoN, especially ***Laura Tennant*** and ***Connie Clare*** for your help and mentorship on numerous occasions. You were the PhD students I aspired to be! To my housemate, ***Beth Woollacott***, for keeping me sane on this crazy PhD journey with gin, walks and laughter. And of course, to ***Chloe Geoghegan****,* we came so far together and your courage to choose your path I will always admire.

To the amazing members of the Early Career Council at the British Society of Animal Science, for providing me with a community to share the turbulent experiences of a PhD with and giving me more confidence.

Finally, to my boyfriend, ***Josh***, thank you for being by my side through all the everyday highs and lows of my PhD; your focus and determination inspire me to achieve my own successes. But most of all, thank you to my family for believing in me, especially my parents. Without your unconditional love and support, I would not have gotten this far.

Funding statement

Thank you to the University of Nottingham for awarding me a PhD studentship as match-funding for the AHDB Dairy Research Partnership on Animal Health Welfare and Nutrition. AHDB Dairy (https://ahdb.org.uk/dairy) is a levy-funded, not-for-profit organisation working on behalf of British dairy farmers and a division of the Agriculture and Horticulture Development Board.

Thank you to CIEL for the research equipment and to AB Vista for funding the calf study in Chapter Four.

Publications

Conference proceedings associated with PhD

Ross LH, Garnsworthy PC and Margerison JK (2020) 80. Effect of calfhood respiratory disease on rearing targets in Holstein-Friesian dairy heifers. *Advances in Animal Biosciences,* 11, 81. The Challenge of Change, British Society of Animal Science. Cancelled, 30 March – 1 April 2020.

Ross LH, Garnsworthy PC and Margerison JK (2021) 07. Effect of age at first calving on longevity and lifetime performance in Holstein-Friesian dairy heifers. *Developing Talent Proceedings*, 1, 10. The Challenge of Change – The New Normal? British Society of Animal Science. Virtual, 12 – 15 April 2021.

Ross LH, Garnsworthy PC and Margerison JK (2022) 79. Variation in age at first calving over a twelve-year period in a high-yielding dairy herd. *Animal – Science Proceedings,* 13, 53. The Role of Animals in Human and Planetary Health, British Society of Animal Science. Nottingham, UK, 11 – 14 April 2022.

Abstract

Whole-farm feed efficiency (WFFE) is a novel metric to measure farm performance which accounts for the costs of all animals in a dairy system, including herd replacements, dry cows, and bulls. However, our understanding of current heifer rearing practices in the UK and how they may affect WFFE is limited. This PhD thesis broadly aimed to assess the effect of factors relating to rearing herd replacements which are associated with WFFE. Using the University of Nottingham's Centre for Dairy Science Innovation as a representative of a high-yielding (mean annual milk yield 12,780 L/cow), all-year-round system, data from Holstein-Friesian heifers born between 2007 and 2018 were used to analyse age and live weight (LW) at first calving and how they, one; are affected by calf health, two; influence first lactation performance and three; impact longevity and lifetime performance.

Age at first calving (AFC) is recognised as a key performance indicator in the dairy industry, but the proportion of systems achieving the 730 day (24 month) target has remained low. In study one, mean age and maturity at first calving for the herd met industry targets but only 10% of heifers met both targets. Studies two, three and four demonstrated how rearing performance and AFC are impacted by disease, growth rate and fertility. Study two found four in ten calves contracted a gastrointestinal enteric disorder (GED) for two days between 10 and 15 days of age on average. In the first four weeks of life GED reduced milk replacer intake by 1.0 L/d (p=0.001) and daily LW gain (DLWG) by 0.14 kg/d (p=0.007) and decreased weaning LW by 10% (p<0.001). Reduced milk replacer intake and greater unrewarded visits to the automatic calf feeder were associated with GED (p<0.05) and have the potential to be developed into automated tools for early indication of disease. In study three, bovine respiratory disease (BRD) delayed AFC by 41 days (p<0.001), increasing estimated rearing costs by £708 per heifer (39%). Study four found that heifers which took more than 50 days after first service to be diagnosed pregnant had 2.4% less maturity at first service (p<0.001), took 18 days longer to conceive during first lactation (p=0.021), were 8.5% less likely to calve a second time (p=0.043) and spent 156 fewer days in milk over their lifetime

(*p*<0.001). Study five concluded that heifers must enter the milking herd with sufficient maturity to achieve a high dry matter intake and milk yield during first lactation, but factors which increase feeding and resting time of heifers can further improve first lactation performance. Lastly, in study six, heifers calving at 700 days (23 months) conceived 22 days earlier in their first lactation (*p*=0.034), repaid their rearing costs 254 days sooner (*p*<0.001) and spent an additional 8.2% of their life lactating (*p*=0.003).

In summary, the most efficient heifers in this herd were those that calved at 700 days with sufficient maturity and were fertile. This can be achieved by investing adequate resources into rearing heifers at target growth rates and reducing disease incidence. Costs associated with improved heifer rearing will be returned by increasing lifetime productivity of individual cows. Increasing the proportion of heifers achieving rearing targets will increase heifer rearing efficiency and indirectly improve WFFE of the herd.

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Abbreviations

°C	Degree Celsius
ACF	Automatic calf feeder
AFC	Age at first calving
AFS	Age at first service
AI	Artificial insemination
AMS	Automatic milking system
AYR	All-year-round
BCS	Body condition score
CCC	Climate change committee
CP	Crude protein
d	day
DLWG	Daily live-weight gain
DM	Dry matter
DMI	Dry matter intake
ECM	Energised calf milk
FC	First calving
FCE	Feed conversion efficiency
FCM	Fat-corrected milk
FCS	Faecal consistency score
g	gram
GED	Gastrointestinal enteric disorder
GIT	Gastrointestinal tract
hr	hour
IGF-1	Insulin-like growth factor 1
Ig	Immunoglobulin
IQR	Interquartile range
kg	kilogram
KPI	Key performance indicator
L	litre
LW	Live weight
LWFC	Live weight at first calving

LWSC	Live weight at second calving
MJ	Megajoule
mL	millilitre
ME	Metabolisable energy
MR	Milk replacer
MW	Mature weight
MY	Milk yield
NDF	Neutral detergent fibre
NSAID	Non-steroidal anti-inflammatories
s.c.	subcutaneous
SD	Standard deviation
SE	Standard error
SMP	Skimmed milk powder
UK	United Kingdom
USA	United States of America
VFA	Volatile fatty acid
WFFE	Whole-farm feed efficiency
WOL	Week of lactation

General introduction

Producing safe, nutritious, and sustainable food is a global priority (World Health Organization, 2022). The agricultural industry has historically met the rising demand for food by increasing productivity through intensification (Ritchie and Roser, 2019). However, growing concerns over the environmental impact of current agricultural practices (Poore and Nemecek, 2018; Ritchie and Roser, 2020) and the welfare of farmed animals have required livestock systems to give more precedence to improving their efficiency and becoming more sustainable.

In 2015, world leaders agreed to an international target of net zero carbon emissions by 2050 to combat human-induced global warming (UNFCCC, 2015). It is estimated that dairy cows contribute 3.4% to global greenhouse gas (GHG) emissions, however, efficiencies vary between countries (FAO and GDP., 2018). In the UK, recent figures suggest that agriculture contributes 11% to national GHG emissions (DBEIS, 2022) with enteric methane production from livestock contributing to half of UK agricultural GHG emissions (CCC, 2020b). The Climate Change Committee (CCC) suggested that to achieve net zero in the UK by 2050, there would need to be 64% reduction of GHG between the agriculture and land-use sectors, (CCC, 2020a) which has triggered an urgency for research and development into sustainable strategies to improve the efficiency of agricultural systems.

Feed efficiency, or feed conversion ratio, has been used to measure the environmental impact and profitability of different livestock systems (Wilkinson, 2011). Feed efficiency in dairy cows is a calculation of saleable milk output and dry matter feed input, and can be associated with environmental factors such as land use (Bell *et al.*, 2011), feed sources (Reynolds *et al.*, 2010; Iwaniuk *et al.*, 2015; Kliem *et al.*, 2019) and nutrient excretion (Hoffman *et al.*, 2007). Due to advancements over recent decades in herd management and animal health, nutrition and genetics, the modern dairy cow now produces four times as much milk as her equivalent in 1944 (Capper *et al.*, 2009), and twice as much as her equivalent in 1974 (DEFRA, 2022). As a result, the UK produces similar milk

yields from fewer cows and feed efficiency has increased, but feed costs have remained the highest input for dairy producers, contributing between 45% (Chamberlain, 2012) to 70% (Redman, 2015) of total variable costs.

Studies of feed efficiency normally only consider the milking cows in a dairy system, so any improvements gained in these animals may be mitigated by inefficiencies in other animals on the farm; including dairy-bred beef calves, dry cows, and replacement heifers, which may influence overall feed use and farm profitability. However a recent report suggests dairy producers should calculate their whole-farm feed efficiency (WFFE) which takes account of all animals in a dairy system and can be defined as a measure of milk output (kg per year) per unit of feed input (dry matter (DM) kg per year) of every animal on the farm (Garnsworthy *et al.*, 2019).

The report evaluated WFFE on 20 UK dairy farms and identified significant gaps in the knowledge of youngstock management due to many farms keeping no or incomplete heifer records, particularly for health, live weight and feed data (Garnsworthy *et al.*, 2019). This means that a large majority of the UK dairy industry is potentially overlooking gains in sustainability and profitability from improving efficiency in the rearing period. The main heifer components that were identified as important drivers in WFFE included: heifer morbidity and mortality, heifer growth rates, age at first calving and replacement rate. It is thought that improvements in these components will not only reduce rearing costs and inefficiencies (Boulton *et al.*, 2017), but also increase the lifetime productivity and herd longevity of heifers (Cooke and Wathes, 2014) which will help achieve greater WFFE.

Rearing costs are integral to a dairy system's efficiency and profitability as they are the second-largest input following feed, contributing 20% to variable costs (Heinrichs, 1993), and are directly linked to when a producer begins to see a return on their rearing investments. It is difficult to estimate rearing costs accurately due to variations in systems and lack of heifer data. To date, the most comprehensive UK study, which surveyed 101 dairy farms, estimated that it cost £1819, or £2.31/d, to rear a heifer that calves at 784 days (25.8 mo; Table I), and it took 530 days from first calving to repay that cost (Boulton *et al.*, 2017).

Table I: Summary data showing the duration and cost of rearing dairy heifers during each development period taken from a survey of 101 British farms (Boulton *et al.*, 2017)

	Age at end of period (day)		Total cost (£)		Daily cost (£/day)	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Birth to weaning	62 ± 13	42 – 112	£195.15	£94.64 - 499.80	£3.14	£1.68 - £6.11
Weaning to conception	509 ± 60	365 – 700	£745.94	£295.32 - £1745.85	£1.65	£0.75 - £2.97
Conception to calving	784 ± 60	639 – 973	£450.36	£153.11 - £784.00	£1.64	£0.56 - £2.86
Birth to calving	784 ± 60	639 – 973	£1819.01	£1073.36 - £3070.46)	£2.31	£1.47 - £3.35

Table II: Classification and feed efficiency of UK dairy systems (Garnsworthy *et al.*, 2019)

Descriptor	**Dairy production system**				
	1	**2**	**3**	**4**	**5**
Calving pattern	Spring	Block / All year	Block / All year	All year	All year
Grazing, days	>274	183 to 274	91 to 182	0 to 90	0
Feeding	Limited supplements	More use of supplements	Mixed ration and supplements	Mostly mixed ration	All mixed ration
$WFFE_{ECM}$ (kg ECM/kg Feed DM) [1]	0.99	1.04	1.07	1.08	1.13
$WFFE_{MS}$ (kg Milk Solids/t Feed DM) [2]	72.4	73.6	74.8	75.9	79.3
WFFEe (£ milk income/£ feed costs) [3]	4.15	3.34	2.45	2.58	2.72

[1] $WFFE_{ECM}$ = energy-corrected milk (ECM) yield divided by total feed dry matter (DM) produced on the farm or purchased
[2] $WFFE_{MS}$ = milk solids (MS) yield divided by total feed DM produced on the farm or purchased
[3] WFFEe = income from milk sales divided by variable costs of feed produced and purchased over 12 months

Age at first calving (AFC) is a common key performance indicator (KPI) in the dairy industry as it is easily measurable and requires no animal handling or equipment to record. For this reason, AFC is well studied and has been found to be a major determinant of rearing costs and time to return rearing costs, and affects many factors relating to herd performance.

The benefits of an early AFC were recognised in the 1960s (Clark and Touchberry, 1962; Amir *et al.*, 1967), with 730 days (24 months) generally accepted as the optimum AFC by the global dairy industry in the 1990s (Hoffman and Funk, 1992; Heinrichs, 1993). However, many dairy producers worldwide do not achieve this long-standing target, with mean ages ranging from 745 to 943 days (24.5 to 31 months) (Ojango and Pollott, 2001; Haworth *et al.*, 2008; Brickell *et al.*, 2009c; Cole and Null, 2010; Wu *et al.*, 2012; Froidmont *et al.*, 2013). From an annual UK study of 500 NMR herds, mean AFC in 2020 was 821 days (27 months) and this has not changed since 2015 (Hanks and Kossaibati, 2020).

An interesting outcome of the WFFE survey confirmed that UK dairy producers can be effectively classified into five systems according to days grazing, with fully-housed systems achieving the greatest WFFE in three efficiency metrics (Table II; Garnsworthy *et al.*, 2019). However, there is little published about the prevalence of dairy housing and grazing systems in the UK. Recent estimates from a large survey found that 8.5% of 863 UK dairy farms house their cows all-year-round (AYR), with a further 8% housing just high-yielding or early lactation cows AYR (March *et al.*, 2014). Surveys from other countries report that there is rising interest in transitioning to a fully-housed, AYR system as a means of sustainable intensification and the easier adoption of automation and precision technologies, which have become increasingly popular. For example, uptake of AYR housing has increased from <10% to 30% since 1992 in Dutch dairy farms and from 16% to 70% since 2001 in Danish dairy farms (Reijs *et al.*, 2013). Moreover, in North America, where dairy producers are reportedly global leaders according to annual milk yield per cow (FAO and GDP., 2018), approximately 60% of the lactating cow population is housed AYR (USDA, 2010).

Performance and efficiency of high-yielding British cows in fully-housed, AYR systems is the subject of an ongoing investigation. However, our understanding of heifer rearing practices used in these systems and how they may affect overall farm efficiency and profitability is lacking. The WFFE report found that grazing days were negatively associated with rearing costs (p=0.021) but explained only 31% of the variation (Garnsworthy *et al.*, 2019). Both the report and Boulton *et al.* (2017) concluded that rearing costs are influenced by more than fertility management and farm system classification. Therefore, this thesis broadly aims to increase our knowledge of how UK dairy heifers perform in a high-yielding, fully-housed system and how this impacts rearing costs and efficiency, with a specific focus on the age at first calving.

Chapter 1

Factors affecting age at first calving and its associations with herd performance

This chapter provides an overview of associations between factors in the rearing period, age at which replacement heifers enter the milking herd, and their performance and longevity thereafter. The review will first present interactions between age at first calving (AFC) and lifetime performance, and subsequently its relation to profitability and efficiency of a system. This will be followed by various aspects of heifer rearing which have been found to affect AFC and factors affecting milk yield and survivability, thus culminating in this study's working hypotheses.

1.1 Age at first calving and lifetime performance

1.1.1 Age at first calving and milk yield

Economic return from individual heifers is a key driver to increasing farm profitability. Many studies agree that reducing AFC reduces milk yield in the first lactation (Lin *et al.*, 1988; Losinger and Heinrichs, 1997; Berry and Cromie, 2009b; Storli *et al.*, 2017). This negative relationship can be described as almost linear because reducing AFC from 943 to 700 days (31 to 23 months) reduced 308-d first lactation milk yield in Canadian heifers by 96 kg/mo, or 3.1 kg/d (Lin *et al.*, 1986). The same relationship, but to a lesser effect, was observed in Irish Holstein-Friesians where 305-d first lactation milk yield was reduced by 56 kg/mo, or 1.8 kg/d, between 1125 and 639 days (37 and 21 months) at first calving (Berry and Cromie, 2009a). Likewise, Storli *et al.* (2017) found that heifers calving at 700 days (23 months) produced 2.9 kg/d less milk in their first lactation than those calving at 791 days (26 months). However, some studies have reported a non-linear effect of AFC, where calving after 821 days (27 months) reduced first lactation yields in both Norwegian Red heifers (Storli *et al.*, 2017) and US Holstein heifers (Losinger and Heinrichs, 1997).

Boro *et al.* (2016) found that although heifers calving before 700 days (23 months) produced 11% less milk in their first lactation, there was no adverse effect on subsequent milk yield. Increasing a heifer's herd life is positively associated with their daily lifetime profit ($R^2 = 0.65$), however, increasing lifetime daily yield (LDY) per heifer had a greater effect on profitability than increasing their herd life (Rendel and Robertson, 1950). In terms of LDY, heifers calving

at 669 days (22 months) have been found to yield an additional 2.4 kg/d of milk over their lifetime compared to heifers calving at 1095 days (36 months) (Eastham, 2012). Similarly, Cooke *et al*. (2013) found that LDY increased as AFC decreased, with heifers calving before 700 days (23 months) producing 5295 kg, or 2.7 kg/d, more milk over 5 years of life than heifers calving after 913 days (30 months). However, the association between increased productive life and early AFC has been found to diminish in heifers calving below 639 days (21 months) (Nilforooshan and Edriss, 2004). Overall, literature supports that earlier calving heifers have lower first lactation milk yield but higher lifetime milk yield.

A significant and positive association between first lactation and lifetime milk yield was confirmed by Stassen *et al.* (1991). Equally, heifers with lower first lactation milk yield (<15 L/d) were found to have relatively lower second and third lactation yields (Haworth *et al.*, 2008). Therefore, Haworth *et al.* (2008), suggested that first lactation milk yield may help in the decision-making of retaining low-yielding cows. However, although, lactation of culling was not affected by AFC or first lactation milk yield, no heifer yielding more than 30 L/d survived to third calving, with heifers that yielded between 20 and 30 L/d in their first lactation having the greatest estimated lifetime yield. Supporting this, it has been warned that, while selecting for greater daily first lactation milk yield indirectly gave the greatest response in lifetime performance traits, selecting sires whose daughters have very high yields but short lives may not equate to greater profit since long herd life is a major determining factor of a dairy system's profitability (Jairath *et al.*, 1995).

Days in milk (DIM) have been found to be a useful indicator of lifetime productivity and are positively associated with a reduced AFC. Holstein heifers calving at 700 days (23 months) were found to have 107 more DIM than those calving at 791 days (26 months) (Lin *et al.*, 1988), further supporting a 700 days (23 months) optimum AFC. Froidmont *et al.* (2013) compared DIM as a proportion of total days alive and found heifers calving as early as 548 to 669 days (18 to 22 months) spent 60% of their life in milk. This reduced to 58% for an AFC between 669 and 791 days (22 and 26 months), to 55% between 791

and 913 days (26 and 30 months), and 48% for heifers calving after 913 days (30 months). Cooke *et al.* (2013) used similar calving groups; however, DIM as a proportion of days alive decreased more rapidly as AFC increased so that there was a three-fold difference between extreme calving groups (54% for before 700 days (23 months) and 18% for after 913 days (30 months)). Nevertheless, based on DIM as a proportion of days alive, the results from these two studies suggest that heifers can be calved before 700 days (23 months) for greater lifetime productivity.

1.1.1.1 Lifetime performance and environmental impact

Earlier studies focused on first lactation performance, however, there is a greater need for research on improving lifetime performance, particularly LDY and its associations with environmental impact. Garnsworthy (2004) found replacement heifers contributed 27% to methane emissions and could add an extra 6% to herd emissions due to their larger size and greater numbers if calving later than optimum. Reducing AFC from 821 to 730 days (27 to 24 months) required 12% fewer replacement heifers, which when combined with greater lifetime production and longevity, diluted the economic and environmental cost of rearing replacements. Haworth *et al.* (2008) found heifers calving between 730 and 913 days (24 and 30 months) had a significantly higher longevity index (LI), which was 2.2% higher than heifers calving before 730 days (24 months) and 5.0% higher than heifers calving after 913 days (30 months). The LI was defined as DIM as a proportion of total days alive and therefore expressed the efficiency of individual heifers. However, definition of longevity varies between studies. Haworth *et al.* (2008) calculated total days alive as the difference between date of birth and date of culling, whereas 'herd life' or 'productive life', has been defined as the difference between date of first calving and date of culling (Beaudeau *et al.*, 1995; Tsuruta *et al.*, 2005). These longevity terms cannot be used interchangeably as using Beaudeau *et al*. (1995) and Tsuruta *et al.* (2005) definitions in Haworth *et al.* (2008) study would give heifers surviving one lactation a LI of 100% which would be misleading.

Additionally, herds with a lower proportion of first lactation cows have been found to have greater per-cow milk production and lower greenhouse gas

(GHG) emissions per-kilogram milk (Liang and Cabrera, 2015). In their model of US Holsteins, herds made up of 45% first lactation cows produced 9 to 14% more emissions than herds made up of 15% first lactation cows. Increasing yield per day and yield per cow can improve feed efficiency and reduce environmental impact by diluting maintenance. This is because cows with higher yields partition more energy from feed towards producing milk instead of maintenance and growth (VandeHaar *et al.*, 2016). The rate of genetic gain in recent decades has increased rapidly to produce dairy cows with higher milk yields. This has seen more dairy producers transition to an intensified, high-output system, now only requiring 21% of lactating cows needed in 1944 to achieve the same milk yield (Capper *et al.*, 2009). This has also improved feed efficiency (VandeHaar and St-Pierre, 2006). Likewise, Vandehaar and St-Pierre (2006) showed that reducing the proportion of the lifetime spent unproductive, as a heifer or dry cow, improved lifetime feed efficiency.

1.1.2 Age at first calving and survivability

An older AFC has been associated with lower survivability (Evans *et al.*, 2006; Bach, 2011; Cooke *et al.*, 2013). Heifers completing their first lactation were those with a lower AFC (Wathes *et al.*, 2014) and survival decreased as AFC increased over 669 days (22 months). As AFC increased over 760 days (25 months), proportionally fewer heifers achieved a third calving; this was 70% in heifers calving between 700 and 760 days (23 and 25 months) and 50% in heifers calving after 913 days (30 months) (Cooke *et al.*, 2013). Likewise, increasing AFC from 730 to 821 days (24 to 27 months) increased the odds of either death or culling by 10% (Archer *et al.*, 2013). Bach (2011) found that delaying an AFC of 724 days (23.8 months) by 13 days was enough to significantly impact completing first lactation (R^2=0.14; p<0.05) and heifers could calve as early as 662 days (21.7 months) without compromised survivability. However, others have found that AFC did not directly affect first lactation survivability (Simerl *et al.*, 1992; Ettema and Santos, 2004). Likewise, survivability up to third calving was not affected by AFC in Kenyan heifers, but calving both before 852 days (28 months) and after 1156 days (38 months) increased culling risk, suggesting a non-linear relationship between AFC and

survivability (Ojango *et al.*, 2005). Inconsistencies among studies may be due to small numbers of herds represented in some studies (Simerl *et al.*, 1992; Ettema and Santos, 2004) as well as low variation in AFC (Ettema and Santos, 2004).

Season of calving may influence survivability since heifers that calved in winter or spring had 1.25 and 1.37 greater odds of finishing their first lactation respectively (p<0.05), than those calving in summer and autumn (Bach, 2011). However, there was no association between calving season and stage of lactation when heifers left the herd. This is different to Pinedo and De Vries (2010) who found heifers calving in winter and autumn had lower odds of death and live culling, but only second parity and above cows were included in this study. Ettema and Santos (2004) also found that calving season impacted first lactation survivability, with heifers calving in summer being sold for slaughter significantly earlier in first lactation than heifers calving in autumn, and heifers calving in winter and spring had similar first lactation survivability. However, Sherwin (2017) found heifers calving in summer had the greatest odds (0.82) of finishing first lactation, proving that the association between calving season and AFC remains unclear.

Survivability in terms of rate, age and reason of culling have important financial impacts that can reflect the health and welfare status of animals and the efficiency of dairy systems. The annual culling rate in the UK in 2020 was 28% and culling age was 6 years, which have remained at similar levels since 2017 (Hanks and Kossaibati, 2020). This culling rate is similar to that of other countries which have seen herd demographics shift towards younger ages. Studies in the USA have shown that due to increased culling rates, the average lifetime of a Holstein cow has decreased from 3.4 (Nieuwhof *et al.*, 1989) to 2.8 lactations (Tsuruta *et al.*, 2005). Replacement rate is directly linked to culling rate, both of which depend on several factors, primarily management and fertility (Archer *et al.*, 2013). As a result of fewer lactations, availability of surplus replacement heifers is reduced and replacement rate is increased (Honarvar *et al.*, 2010).

Culls are usually defined as voluntary or involuntary, but Fetrow *et al*. (2006)(Fetrow *et al.*, 2006) redefined culls as: forced culls, where a productive future is deemed unlikely; and economic culls, where replacement with another cow is deemed more economical. It was argued that because many culls are economic, replacement must be a better financial decision for the system. However, Compton *et al.* (2017)(Compton *et al.*, 2017) did not support the assertion of Fetrow *et al*. (2006) that dairy producers make economical-based decisions to replace poor-yielding cows with more productive ones, and instead found producers were reluctant to do this and decisions were associated with disease-related reasons.

High culling rates increase the risk that a heifer will be disposed of before she returns her rearing costs and begins making a profit. Breen *et al.* (2012) suggested that no more than 7% of heifers born alive should fail to calve. However, pre-calving mortality rates in the UK vary between 0 and 29% and on average 11% of heifers born alive fail to calve (Brickell and Wathes, 2011). In another UK study, the mean cost of pre-calving mortality was £140 for every surviving heifer, depending on the whole-farm mortality rate and herd size (Boulton *et al.*, 2017). Therefore, high pre-calving mortality rate reduces profit due to lack of rearing cost return which compromises the financial risk to the dairy enterprise.

First lactation survival is essential as heifers do not return their rearing costs until 530 days post-calving, or 1.5 lactations, on average (Boulton *et al.*, 2017). There have been few large-scale studies in the UK and worldwide to evaluate first lactation survival. Bach (2011) found in a study using 7788 Spanish Holstein heifers, 8.4% of those born alive did not finish first lactation, with 31.4% of failed heifers leaving the herd in the first 50 DIM. In UK and US studies this was higher, with 16% (Sherwin *et al.*, 2016) to 28% (Brickell and Wathes, 2011) and 17% (Tsuruta *et al.*, 2005) of heifers born alive not finishing first lactation respectively. It has been suggested that first lactation culling rate should be no more than 10%, indicating that current rates are too high (Breen *et al.*, 2012). Sherwin *et al.* (2016) concluded that for individual heifers, the likelihood of

finishing first lactation was related to AFC, overall farm culling rate and calving season.

Comparable results were found for survival beyond first lactation. Studies using Holstein heifers found that between 47% (Tsuruta *et al.*, 2005) and 58% (Brickell and Wathes, 2011) of heifers born alive failed to complete third lactation, with few (3%) surviving beyond fifth lactation (Tsuruta *et al.*, 2005). A longer productive life is directly related to greater number of lactations which is associated with total profit and profit per day of life (Ducrocq *et al.*, 1988). Honarvar *et al.* (2010) stated that a short productive life leads to high replacement costs and limits breeding selection. Directly selecting for longevity traits is difficult in dairy cows since heritability is low (0.01–0.30; Hu *et al.*, 2021), but using traits correlated with longevity correlations such as udder depth and teat length might overcome this (Setati *et al.*, 2004).

1.1.3 Age at first calving and subsequent fertility

Poor fertility has been found a major culling reason of heifers in their first lactation (Esslemont and Kossaibati, 1999; Brickell and Wathes, 2011). AFC has been associated with subsequent fertility and survivability, with heifers calving between 700 and 760 days (23 and 25 months) having fewer days open (Ettema and Santos, 2004), shorter calving intervals (Ettema and Santos, 2004; Eastham, 2012) and greater herd longevity (Bach, 2011; Cooke *et al.*, 2013). However, another study found no effect of age on any measure of reproductive performance during the first lactation (Simerl *et al.*, 1992). Cooke *et al.* (2013) also found no significant effect of AFC group on days to first service or first service conception rate (CR) in the first lactation, but age at second calving was positively associated with AFC, with over 300 days between heifers calving at <700 and >913 days (<23 and >30 months). Although, there was a tendency (p=0.075) for heifers calving at >913 days (>23 months) requiring greater serves per conception (4.7 ± 1.7) compared to the three groups of younger calving heifers (mean range: 2.2 to 2.6) and consequently, heifers calving >913 days (>30 months) had the greatest calving to conception interval (170 ± 18 days, p=0.072). Cooke *et al.* (2013) indicated that as heifers calving in the oldest group had the highest pre-calving body condition score (BCS) of 3.8 to

3.9, these animals had become too fat. It is thought that heifers calving with higher body condition subsequently mobilise more tissue which has deleterious consequences on fertility (Wathes *et al.*, 2008). Thus, it was suggested that heifers calving between 700 and 760 days (23 and 25 months) tended to have the best fertility in their first lactation as they were closest to the correct body condition at first calving.

1.1.4 Age at first calving, rearing costs, and profitability

The cost of rearing replacement heifers is 20% of total milk production costs and the second largest expense following feed costs (Heinrichs, 1993). However, although this is the case, heifer rearing remains one of the least understood processes. A recent study estimated this cost to be £1,819 per heifer calving at 784 days (25.8 months) and an additional £2.87 is incurred for every day over 784 (Boulton *et al.*, 2017). In terms of milk sales, herd replacement costs were found to equate to between 2.6 and 3.8 ppL (DairyCo, 2013). A dairy system must invest in feed, labour, and capital to rear replacements without seeing a return until the heifer is halfway through her second lactation (Boulton *et al.*, 2017). However, rearing cost return was found to range between 1.4 and 6.4 lactations, with 10% of farms requiring at least 3 lactations to return rearing costs. With UK dairy cows averaging 3.5 lactations (Hanks and Kossaibati, 2020), it is concerning that some farms have little margin between age at returning rearing costs and age at culling. However, average cow milk yield, farmgate price of milk and subsequent fertility also need to be considered when calculating this margin.

A younger AFC is beneficial as it generally reduces rearing costs (Tozer and Heinrichs, 2001) and returns rearing costs earlier. Using an estimate of £2.31/d up to calving at 791 days (26 months) and £2.87/d thereafter (Boulton *et al.*, 2017), reducing the current UK national AFC of 821 days (27 months) (Hanks and Kossaibati, 2020) to the target of 730 days (24 months), could reduce estimated rearing costs by 13%. Tozer and Heinrichs (2001) found a similar decrease of 18% in rearing costs when AFC was reduced from 760 to 639 days (25 to 21 months). Eastham *et al.* (2018) found the difference between milk yield revenue and rearing costs to increase by £32 and £19 when AFC was

reduced from 791 days (26 months) to 730 and 669 days (24 and 22 months) respectively. Above 791 days (26 months) resulted in a negative difference due to increased rearing costs.

AFC has been found to account for 35% of rearing cost variability (Boulton *et al.*, 2017), however, measurement of AFC cannot directly identify issues and inefficiencies in the rearing process. It was concluded that economic efficiency of rearing processes cannot by calculated on measurements such as average calving age and LW alone (Mourits *et al.*, 2000a). Factors contributing to the distribution of these measurements, and the number of involuntarily and voluntarily replacements, need to be explored further to provide more relevant information on heifer rearing efficiency.

Investment in replacement heifers and providing better heifer management must be recouped later if the farm is to remain profitable. Some clear contributors to rearing costs emerge from comparison of studies. The greatest contributor is feed cost (Tozer and Heinrichs, 2001), contributing approximately 37 to 60% depending on inclusion of grazing (Mourits *et al.*, 1999; Boulton *et al.*, 2017). Mourits *et al.* (1999) concluded that growing pre-pubertal heifers at 0.7 kg/d to reduce age of puberty to 213 days (7 months), increased profitabliity in relation to feed costs as daily LW gain (DLWG) above this threshold exceeded savings in feed costs. Feed cost was followed by labour cost, which ranged from 9% (Kingshay, 2013) to 32% (Mohd Nor *et al.*, 2012). Costs associated with reproduction and disease were found to be 4.4% and 4.1% respectively (Boulton *et al.*, 2017). When looking at the rearing period in three distinct phases; birth to weaning, weaning to conception, and conception to calving, birth to weaning was found to be most expensive due to higher feed and labour costs over a shorter period (Table I). Effective rearing management is critical in high-yielding herds to ensure that heifers become healthy and robust adult cows and secure the integrity of the future milk herd. It has been suggested that even when cows have high levels of production, they may not realize expected economic benefits due to overall decline in other traits such as fertility, longevity, and health (Lee and Kim, 2007).

1.1.5 Targets and objectives of heifer rearing

Despite the 730 days (24 months) AFC recommendation having existed for several years, many farms are still not achieving this. An analyses of age and LW at first calving for US Holsteins showed that only 2.7% of dairy farms calved before 730 days (24 months) and heavier than 550 kg (Losinger and Heinrichs, 1997). In the UK, Cooke *et al.* (2014) found that half of heifers calved at less than 791 days (26 months), confirming reports from other countries (Pirlo *et al.*, 2000; Evans *et al.*, 2006; Hare *et al.*, 2006). Many reasons have been proposed for the disparity between recommended targets and actual AFC and LW at first calving (LWFC) such as insufficient DLWG, delayed age at first service (AFS) and underestimation of heifer LW at which mating should take place (Duplessis *et al.*, 2015). Particularly in all-year-round (AYR) calving systems, where producers aren't tied to block calving, there is a temptation to increase length of the rearing period for heifers that aren't considered big enough for mating at 395 to 456 days (13 to 15 months), with producers holding them back until they reach what they consider to be an 'adequate' size (Dingwell *et al.*, 2006).

In addition, some researchers have questioned the validity of these recommendations, arguing that these recommendations, produced universally for the dairy industry, may be inappropriate in relation to the management system and capability of individual farms (Wathes *et al.*, 2014). With so much conflicting evidence regarding effects of reduced AFC on future production and lack of implementation of these targets, there is a clear need to provide farmers with data demonstrating the long-term benefits and possible economic advantages associated with an earlier calving age.

Hoffman (1992) concluded that the total applied dynamics of heifer management is a combination of biology, economics, productivity, and profitability. From previous studies, Hoffman (1992) suggested six key concepts to rearing heifers. One; rearing costs can be reduced by reducing AFC (Heinrichs and Swartz, 1990; Crowley *et al.*, 1991). Two; reducing AFC requires increased planes of nutrition (Amir *et al.*, 1967; Gardner *et al.*, 1977; Little and Kay, 1979; Bettenay, 1985). Three; increased planes of nutrition negatively influence pre-pubertal mammary development and potential milk yields

(Sejrsen *et al.*, 1982a; Harrison *et al.*, 1983; Stelwagen and Grieve, 1990). Four; increased LWFC reduces incidence of dystocia (Thompson *et al.*, 1983; Erb *et al.*, 1985). Five; increased LWFC has a positive effect on first lactation milk yield (Clark and Touchberry, 1962; Fisher *et al.*, 1983; Lin *et al.*, 1985; Keown and Everett, 1986). Six; increased LWFC has negative effects on feed efficiency (Sieber *et al.*, 1988). These concepts need to be reviewed over time, but the main objective of heifer rearing that still stands for dairy producers is to grow healthy herd replacements using strategies which minimise rearing costs but maximise future milk yield potential (Gabler *et al.*, 2000; Tozer and Heinrichs, 2001).

1.2 Factors affecting age at first calving

1.2.1 Nutrition and growth

To calve at 730 days (24 months) of age and with LW between 550 to 625 kg (Cooke and Wathes, 2014), a daily LW gain (DLWG) target of at least 0.75 kg/d is required throughout the rearing period. Dairy producers are encouraged to grow heifers faster to conceive by 456 days (15 months) and reap the economic benefits of an earlier calving age (Boulton *et al.*, 2017). However, DLWG has found to be highly variable even in heifers within the same farm, and is highly influenced by management, nutritional and health factors (Brickell and Wathes, 2011).

1.2.1.1 The neonatal calf and colostrum feeding

In the UK, it is advised to deliver colostrum according to the three ‘Qs’; quality, quantity and quickly (AHDB, 2015). High quality colostrum should contain no less than 500 mg/mL immunoglobulin (Ig) G (Patel *et al.*, 2014) with a bacterial count of <100,000 colony forming units (cfu) per ml (McGuirk and Collins, 2004). Calves should receive colostrum within the first two hours of life at 10% of the calf’s birth weight, approximately four litres (Patel *et al.*, 2014). However, more recently this has been updated to the five ‘Qs’ to include squeaky clean and quantify (Geiger, 2020). Dairy systems are now encouraged to appropriately store colostrum so that it does not exceed a bacterial count of

100,000 cfu/mL or a coliform count of 10,000 cfu/mL, and take blood tests at 24 hrs of life to check serum IgG levels. This is because intestinal absorption of colostral immunoglobulins is most efficient in the first few hours of life and declines rapidly to half after 12 hrs of life (Davis and Drackley, 1998; Weaver *et al.*, 2000).

Studies have shown a positive association between colostrum management and pre-weaning growth (Davidson *et al.*, 1981; Nocek *et al.*, 1984; Bradley and Niilo, 1985), and a possible improvement in first lactation milk production (DeNise *et al.*, 1989; Van Amburgh *et al.*, 1998). However, these associations will be examined in more detail later in this chapter. It has also been noted that producers who had already adopted good colostrum management were more likely to be practising other good practices, and the best predictors of youngstock management practices were often associated with each other (Winder *et al.*, 2018). Additionally, Bazeley *et al.* (2015) found birth weight ranged between 24 and 55 kg in Holstein-Friesian heifers and had a significant positive correlation with subsequent LW measurements. Epigenetic programming may contribute to variation in birth weight; therefore, it is worth considering the effect of dam nutrition on heifer growth. Lastly, Wathes *et al.* (2017) suggested that restricted growth in utero could not be compensated post-natally. This provides sound evidence that providing premium nutrition to support high growth and good health is key to achieving the correct calving.

1.2.1.2 The pre-weaned calf and milk feeding

A calf is a pre-ruminant at birth with no capability to digest starch, so initially relies solely on the abomasum, which makes up 70% of the neonatal digestive tract, to utilise milk proteins and carbohydrates (Radostits and Bell, 1970). Only after a few days does the calf begin producing enzymes which digest other non-milk proteins and non-lactose carbohydrates thus enabling it to utilise starch and solid feed. The transition to having the capacity to deal with non-milk ingredients can take two to three weeks. When feeding calves at this early age, nutritional regimes must target development of the gastrointestinal tract (GIT) and rumen microbes. Recent literature indicates that providing more milk early in life can provide several benefits, such as greater pre-weaning DLWG

(Soberon *et al.*, 2012; Johnson *et al.*, 2018), reduced disease incidence (Khan *et al.*, 2011b; de Passillé *et al.*, 2016), higher solid feed intake when combined with an appropriate weaning strategy (Jasper and Weary, 2002; Hammon *et al.*, 2020), reduced AFC (Davis Rincker *et al.*, 2011a; Mohd Nor *et al.*, 2013), and increased milk yield (Drackley *et al.*, 2008; Soberon *et al.*, 2012). Heifers with a greater DLWG between 30 and 183 days (1 and 6 months) of age calved earlier, with those calving before 700 days (23 months) of age achieving 0.85 kg/d compared to heifers calving between 791 and 913 days (26 and 30 months) of age achieving 0.66 kg/d (Brickell *et al.*, 2009a). Similarly, calves fed for a pre-weaning DLWG of 0.64 kg/d conceived and calved at a younger age when inseminated at the same LW as calves with growth rates of 0.44 kg/d (Davis Rincker *et al.*, 2011a). In contrast, Morrison *et al.* (2012) found no effect of increasing DLWG by increasing pre-weaning feeding level on subsequent calving age.

Milk feeding strategies have a significant impact on DLWG and calf morbidity and mortality (Soberon *et al.*, 2012). Traditional milk feeding programmes centred around restricted feeding, with calves fed at around 10% of their LW, approximately 4 L/d, to encourage starter intake as soon as possible (Lammers *et al.*, 1999). However, research found that this negatively impacted growth rate (Kertz *et al.*, 1979; Jasper and Weary, 2002; Soberon *et al.*, 2012). This has resulted in producers instead choosing to implement moderate or intensive milk feeding programmes where calves are fed at 16 to 20% of LW, or approximately 8 L/d (Akins, 2016), especially in the first few weeks of life when calves are unable to digest solid feeds. Calves that were offered warm milk replacer *ad libitum* were found to consume up to 14 L/d and gained up to 1.0 kg/d (Bleach *et al.*, 2006).

Although high milk feeding levels may increase pre-weaning costs, intensive feeding of milk or milk replacer improves pre-weaning DLWG that results in greater weaning LW (Jasper and Weary, 2002; Bleach *et al.*, 2006), skeletal frame (Cowles *et al.*, 2006; Stamey *et al.*, 2012) and earlier attainment of puberty (Shamay *et al.*, 2005), which all contribute to a lower AFC (Raeth-Knight *et al.*, 2009), and may increase first lactation milk yield (Drackley *et al.*,

2008). Most skeletal growth occurs during the pre-pubertal period (Heinrichs and Hargrove, 1987), which is also when feed conversion rate has been found most efficient (50%; Bach and Ahedo, 2008). Therefore, this period provides the greatest opportunity for enhancing skeletal growth and growth efficiency. However, increased growth rate in accelerated programs before weaning are not guaranteed to carry through to mating age, particularly when early or abrupt weaning methods are used (Sweeney *et al.*, 2010; Eckert *et al.*, 2015). Atkinson *et al.* (2017) recommended that future studies follow calves after weaning to better identify the effects of weaning practices on subsequent growth and health.

Milk replacers may have various sources of protein and carbohydrates. DLWG varies according to milk replacer composition, and volume and frequency at which it is offered. Whole milk contains about 22.6 MJ of metabolisable energy (ME) per kg of dry matter (DM), which means that a calf requires about 0.33 kg of milk solids (2.6 L of fresh milk, assuming 12.5% solids content) for maintenance alone (Drackley, 2008). Most milk replacers are lower in fat content than whole milk so they have less ME per unit of DM (typically 16.7 to 19.7 MJ ME/kg DM); thus, a calf will require more milk replacer DM just for maintenance. Calves on an intensive high solid, high feeding milk replacer diet (28% crude protein (CP), 18% fat) reached calving almost a month earlier than those on a conventional milk replacer diet (20% CP, 20% fat) (Raeth-Knight *et al.*, 2009). Comparable results were found by Hill *et al.* (2009) who observed maximal DLWG and starter intake when feeding calves a milk replacer with 17% to 20% fat, and 27% protein. Bascom *et al.* (2007) found that calves fed whole milk had the highest DLWG and feed conversion efficiency (FCE) compared with calves offered milk replacer. This is in keeping with previous research, showing greater growth rates in calves fed whole milk and milk replacer with additional amino acids (Hill *et al.*, 2008c; Margerison *et al.*, 2013).

Introducing starter feed

A good quality, palatable starter is key to encourage high feed intake and DLWG. This is because highly palatable starter feeds that contain easily fermentable carbohydrates stimulate rumen development through changes in

the epithelium of the forestomach (Baldwin *et al.*, 2004; Drackley, 2008). Calf starter varies in grain source and inclusion level (Hill *et al.*, 2008b; Khan *et al.*, 2008), physical form (Bach *et al.*, 2007; Montoro *et al.*, 2013) and extent of processing (Bateman *et al.*, 2009), which can affect palatability and intake (Montoro and Bach, 2012).

However, results comparing physical form of starters (textured versus pelleted) are inconsistent in young calves, particularly as “textured” is not clearly defined in the literature nor the specific benefits of textured feed. Some studies suggest that starter feeds which have over 75% of particles greater than 1,190 µm in length are beneficial because high amounts of fine particles reduce solid feed intake and DLWG (Hill *et al.*, 2008a). This agrees with Bach *et al.* (2007) and Porter *et al.* (2007) who found calves fed a coarse starter had a higher solid feed intake than calves fed a pelleted starter. However, Bateman *et al.* (2009) reported no difference in intake between pelleted and textured starters. Disparities among these studies could be attributed to differences in processing methods and the physical and chemical properties of the starter feeds used.

Increasing milk-feeding volume is found to reduce starter intake around weaning compared to calves offered conventional milk volumes (Huber *et al.*, 1984; Jasper and Weary, 2002; Brown *et al.*, 2005; Cowles *et al.*, 2006; Quigley *et al.*, 2006; Raeth-Knight *et al.*, 2009). As a result, DLWG post-weaning may be reduced (Brown *et al.*, 2005), but this effect is debated. Cowles *et al.* (2006) did not see a difference in LW post-weaning between calves fed an intensive or conventional diet but found that calves fed an intensified diet had greater skeletal size 14 days post-weaning for both hip height and hip width in comparison to calves fed a conventional diet. However, calves allowed to suckle from a dam between 5 to 42 days of age did not consume forage or concentrate offered *ad libitum* during this period, and lost LW after 42 days due to weaning stress and poor adjustment to solid feed (Bar-Peled *et al.*, 1997). This may be because starter intake has been found to account for 65% of variation in total gain of LW and estimates of digestible nutrient intake accounted for 88% of variation in final metabolic LW (Kertz *et al.*, 1979). In addition, lower starter intakes during the pre-weaning period in calves

consuming the intensive diet may have resulted in slower rumen development, possibly causing less efficient growth early in the post-weaning period. Additionally, calves fed an intensified milk feeding level had softer faeces which was thought to be due to the low fibre levels since they consumed half as much starter as calves fed a conventional milk feeding level (Davis Rincker *et al.*, 2011a). However, bucket-fed calves offered *ad libitum* milk had greater milk intakes with no detrimental effects on intake of solid food after weaning when compared with milk feeding by bucket twice daily at 10% of LW (Jasper and Weary, 2002).

Season of birth influences starter intake. Compared to calves born in spring and summer, calves born in autumn and winter had greater starter intake (48.3 versus 42.8 kg), greater LW (77.5 versus 75.1 kg), and higher DLWG (0.66 versus 0.63 kg/d) at 56 days of age than calves born in spring and summer (Chester-Jones *et al.*, 2017). These results agree with those of Place *et al.* (1998), who found that calves born in winter tended to have greater DLWG than those born in other seasons.

Feed intake and weaning

Pre-weaning calf starter intake has been closely correlated with DLWG during the week after weaning (Stamey *et al.*, 2012) and is necessary for continued high levels of growth levels in the first few months of life (Cowles *et al.*, 2006; Bach *et al.*, 2013). This is to ensure an adequate nutrient intake to continue to grow at an equal or greater rate than before weaning (Margerison and Downey, 2005; Wathes *et al.*, 2014). Unless the heifer is ready to transition to a solid diet there will be a growth check at this stage which may negate any early beneficial effects of good pre-weaning growth (Khan *et al.*, 2011a). Step-down weaning can encourage greater starter intakes in intensively fed calves and alleviate post-weaning LW loss (Khan *et al.*, 2007; Sweeney *et al.*, 2010), but effects on health may be more complicated to resolve. Additionally, lifetime production and culling age were positively associated with age at which starter intake was consumed above 0.91 kg/d (Heinrichs and Heinrichs, 2011). Therefore, weaning dairy heifers from milk is more successful when they achieve a LW double their birth weight (Soberon *et al.*, 2012) and, more importantly, consume

more than 1.5 kg fresh matter of starter daily for three consecutive days. Recent advances in feeding equipment have allowed development of automated milk and calf feeders. These machines collect feed intake data, which can help producers to wean calves based on solid feed intake.

Provision of forages, such as hay and chopped straw, from three weeks of age, is associated with higher DLWG and starter intake both pre-weaning (Khan *et al.*, 2011a; Dennis *et al.*, 2012; Castells *et al.*, 2013) and post-weaning (Imani *et al.*, 2017) because of increased rumen development (Dennis *et al.*, 2012), pH, DM intake (DMI) and FCE (Coverdale *et al.*, 2004). Better rumen development and solid feed intake pre-weaning led to a better transition to a solid diet as outlined by Khan *et al.* (2011). Starter stimulates the rumen to become more metabolically and physically developed (Khan *et al.*, 2007) as the functional characteristic that drives development of the rumen is the fermentation that starts once the calf begins consuming solid feed. The microorganisms in the rumen ferment solid feed to produce volatile fatty acids (VFAs), which stimulate growth of rumen papillae so the calf can use the products of microbial fermentation for energy. Then the calf can be weaned. Post-weaning forage provision needs to be highly digestible with high DM and sufficiently able to stimulate rumen fermentation products to achieve higher growth rates (Dennis *et al.*, 2012) generated by greater DMI (Khan *et al.*, 2011a; EbnAli *et al.*, 2016). Additionally, Heinrich *et al.* (2005) found that a lack of good quality forage was associated with a later AFC.

1.2.1.3 The weaned calf

Literature on feeding level and heifer growth rate is mainly focused on the pre-weaning stage of the rearing period (Sejrsen and Purup, 1997; Van Amburgh *et al.*, 1998; Davis Rincker *et al.*, 2011b; Soberon *et al.*, 2012; Gelsinger *et al.*, 2016). Studies which explore growth and nutrition between weaning and calving often use crossbred or beef heifers. For example, Pereira *et al.* (2017) (Pereira *et al.*, 2017)found that feeding an energy-dense diet to Nelore-Hereford crossed heifers after weaning resulted in greater DLWG and lower age at puberty. Rincker *et al.* (2011) also associated higher nutritional levels in weaned Holstein heifers with attainment of puberty and suggested the post-weaning

period should be optimised for meeting LW targets. Likewise, a study using pasture-based Holstein-Friesian and Jersey heifers found that post-weaning DLWG had a greater influence on LW, body length, wither height and hearth girth throughout the rearing period than weaning age (Costigan *et al.*, 2022). Nevertheless, excessively conditioned heifers (BCS >3.5) are not of productive benefit and only result in increased risk of calving difficulties and metabolic disorders. Mourits *et al.* (1999) suggested the optimum policy is most economical when heifers are reared at modest levels pre-pubertally, inseminated early then reared at higher levels post-pubertally, whilst preventing excessive body condition by monitoring at regular intervals.

Dystocia and calving weight

Calving difficulties, also known as dystocia, can be a significant problem for dairy producers and can occur in 2% to 7% of dairy animals (Mee, 2008a). There is a higher prevalence in heifers than in cows (Rumph and Faust, 2006), and mortality rates both during and after birth are considerably higher for heifers, 11% compared with 4.6% for cows (Johanson and Berger, 2003). Dystocia is influenced by foetal size and the dam's age, relative maturity, and pelvic width, and can be experienced in both small and large animals. It can occur due to inadequate skeletal maturity, especially if the dam is calving at less than 730 days (24 months) of age (Hansen *et al.*, 2004). Thompson *et al.* (1983) and Erb *et al.* (1985) found a negative correlation between LWFC and dystocia. However, Hoffman *et al.* (1996) found no difference in dystocia for heifers under different post-pubertal feeding regimens with AFC of 627 or 718 days (20.6 or 23.6 months). But in the same study, delaying mating to increase AFC by about 60 days (2 months) resulted in a higher incidence (p<0.01) of dystocia, and higher BCS was suggested as the main reason.

It is therefore important for producers to avoid excessive DLWG in the pre-mating period (Wathes *et al.*, 2008). Ideally, heifers should be 90% mature weight (MW) pre-partum as this reduces incidence of foetal-maternal disproportion dystocia, common within heifers where the pelvis is not wide enough to calve safely (Holm *et al.*, 2014). Rapid growth can be indicative of a larger pelvis area which is negatively associated with dystocia, and Holm *et al.*

(2014) found pelvimetry is a useful culling tool to aid in management of dystocia in pre-mated heifers. Additionally, calving difficulty is likely to impair fertility during the first lactation (Thompson *et al.*, 1983) and increase risk to developing health problems (Erb *et al.*, 1985). Selecting bulls for calf size and calving ease can be used in management strategies against dystocia (Bellows *et al.*, 1971; Klassen *et al.*, 1990), but adequate LW and frame size at calving is more critical.

1.2.2 Measuring growth

Heifers that grew well in the first 183 days (6 months) of life were much more likely to reach LW targets for mating and calving (Cooke *et al.*, 2013; Bazeley *et al.*, 2016), so monitoring heifer growth provides the most direct evidence of heifer performance throughout the rearing period as well as excellent information to predict future performance of heifers (Breen *et al.*, 2012). However, it is unclear how many dairy producers track heifer LW or set specific targets during the milk-feeding period. In addition, large variation can exist between heifers on the same farm, meaning that although some heifers may be achieving target DLWG, breed and genetic variance mean this may not be the case for all heifers (Akins, 2016; Sherwin *et al.*, 2016). Published data are available to provide target LW and growth rates for animals of different ages and different growth patterns for each breed should be considered when formulating LW targets and growth rates (Handcock *et al.*, 2019).

Various measures of growth can be used, including LW, withers or hip height, pelvis width and heart girth. There is a direct correlation between wither height (Bach and Ahedo, 2008) and pelvis area (Holm *et al.*, 2014) and LW of growing heifers, which in turn can be used to measure growth rate. However, Dingwell *et al.* (2006) concluded that weighing heifers on a calibrated electronic scale is the easiest and most accurate method of measuring growth. Duplessis *et al.* (2015) indicated that routinely recording heifer LW in three month intervals, evenly spread from birth to first calving, provided a sufficiently good description and prediction of growth and that more frequent recording may not be economically justifiable nor necessary. Key times for weighing heifers are at birth, after weaning and before the start of mating. Although these times represent a gold standard, practical experience has shown that any LW data

are better than none to enable farmers to make rational decisions about heifer management, so heifer weighing can be slotted in with other husbandry tasks to minimise inconvenience and time (Bazeley *et al.*, 2016).

1.2.3 Early calf health

Health of a calf during its first 183 days (6 months) of life has a significant effect on its DLWG and future performance (Donovan *et al.*, 1998b). This review will focus on the most common diseases experienced during early life; gastrointestinal enteric disorder and bovine respiratory disease.

1.2.3.1 Gastrointestinal enteric disorders

Gastrointestinal enteric disorder (GED) is not a singular disease entity, but a clinical syndrome associated with diseases that result in scour (Kumaresan *et al.*, 2012). It is most prevalent in the first 30 days of life (Virtala *et al.*, 1996a; Svensson *et al.*, 2006), and is the main cause of mortality in calves up to 14 days of age (Bruning-Fann, 1992; Sivula *et al.*, 1996) and responsible for a third of pre-weaned heifer deaths (Figure 1.1). In the UK, there is little information about GED incidence, however it is estimated that over a third of all calves are affected by scour to varying degrees during the rearing period, and average incidences of GED in other countries, including the USA, Canada, Holland, and Sweden were between 10 and 25% (Johnson *et al.*, 2011).

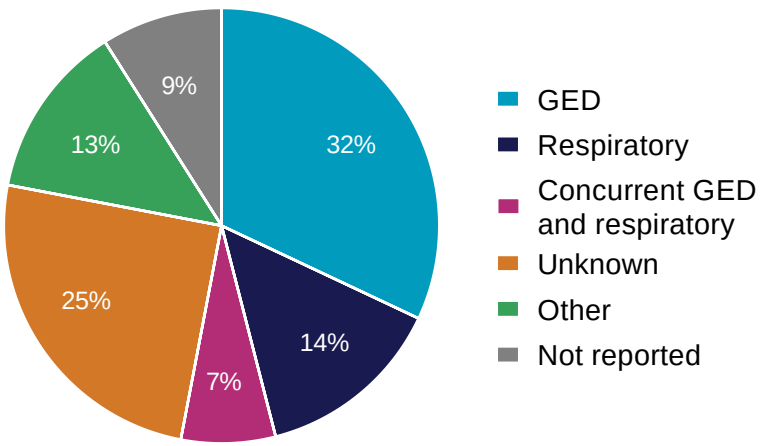


Figure 1.1: Causes of heifer calf mortality. Adapted from Urie *et al.* (2018)

Aetiology

Causes of GED can be categorised as either non-infectious or infectious (Stoltenow and Vincent, 2003). The main infectious causes are viral: rotavirus and coronavirus; parasitic: *Cryptosporidium parvum* and *Coccidiosis;* and bacterial: *Escherichia coli* (Figure 1.2), with rotavirus and *Cryptosporidium* representing over half of scour cases in the UK (APHA, 2012-2020).

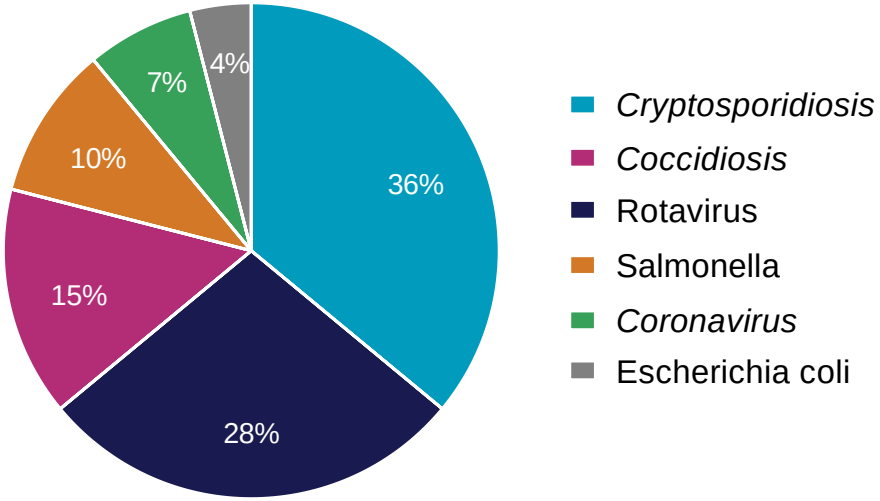


Figure 1.2: Pathogens causing calf scour. Adapted from APHA, 2012-2020.

Most of these infectious agents are commonly shed in faeces of healthy cows and only animals that have inadequate antibody protection will present clinical disease (Trotz-Williams *et al.*, 2007; Coklin *et al.*, 2010; Zhao *et al.*, 2014). In the first 7 days following birth, enterotoxigenic *Escherichia coli* is the main cause of GED (Table 1.1). An overgrowth in *Escherichia coli* has been observed in the small intestines of calves with GED, suggesting dysbiosis in gut microbiota (Constable, 2004)**.** The infectious agent then attacks the lining of the calf's intestine, reducing absorption of fluids and essential nutrients. This creates an electrolyte imbalance causing the calf to scour and potential LW loss (Taylor *et al.*, 2017). Death in scouring calves usually occurs from dehydration because of acidosis and loss of electrolytes and fluids. Identification of infectious agents which cause scours is essential for implementing effective

preventative and treatment measures (Stoltenow and Vincent, 2003; Kumaresan *et al.*, 2012).

Table 1.1: Main infectious causes of calf scour and their symptoms. Adapted from (Huvepharma, 2019)

Infectious agent	Age on onset	Symptoms
Escherichia coli	Commonly: 1 to 7 days	Effortless passing of yellow to white faeces
Rotavirus	Commonly: 3 to 21 days Possibly: 0 to 28 days	Watery brown to light green faeces, blood, and mucus
Coronavirus	Commonly: 5 to 21 days Possibly: 0 to 28 days	Watery, yellow faeces
Coccidia	Commonly: ≥ 7 days	Blood-tinged faeces
Cryptosporidium	Commonly 7 to 21 days	Watery brown to light green faeces, blood, and mucus

Non-infectious causes may also be described as 'predisposing' factors as they are mainly associated with management practices surrounding the dam, the newborn environment and colostrum. These include, but are not limited to; vitamin A deficiency in the dam during late gestation (Kume and Toharmat, 2001); wet and cold calving conditions (Roland *et al.*, 2016b; Kozat, 2018); poor calving pen hygiene (Mee, 2008b); leaving the calf with the dam for more than an hour; and inadequate quantity and/or quality of colostrum, particularly if the dam is a heifer. The incidence and severity of the disease is highly dependent on the level of colostral protection. Understanding the multifactorial dynamic of non-infectious causes is therefore critical to effectively control infectious causes.

Nutritional scour is regarded as another form of non-infectious scour and is most likely caused by feeding management or stress (Stoltenow and Vincent, 2003). Stress to a calf reduces acid secretion into the abomasum, which decreases clot-forming and consequently milk protein digestion (Moran, 2008). Moran (2004) relates stress to feeding management such as overfeeding or irregular feeding, and calves reared on milk replacers are more prone to scours

than those reared on whole milk. This is because sudden changes in the concentration of milk replacers, incorrect milk temperatures or mixing, or a poor quality milk replacer can contribute towards feeding stress. Nutritional scours can also affect older calves, particularly around weaning if rumen development is incomplete or if good quality forage is not offered from an early age (Stoltenow and Vincent, 2003; Meganck *et al.*, 2015). This can be described as 'peri-weaning scour syndrome', however, the aetiology of this condition is not fully understood (Jones, 2000; Mason, 2003). Blowey (1992) suggested that abrupt feed changes or feeding concentrates with high starch levels or designed for adult dairy cows may be related.

Diagnosis and treatment

GED is typically diagnosed by visually assessing faecal consistency and may be scored using a scale as described by McGuirk (2008) and shown in Figure 4.3. Calves which have a faecal consistency score of two or above are said to have GED.

An appropriate oral rehydration solution (ORS) can correct acidosis and dehydration by restoring fluid balance, lost electrolytes, and essential nutrients (Brooks *et al.*, 1996; Wilms *et al.*, 2020). Wilms *et al.* (2020) indicated that the tonicity of both the ORS and milk replacer needs to be considered before administering the ORS. This is because milk replacer is often hypertonic, so when mixed with a hypertonic ORS, high osmotic pressure is created in the small intestine which prevents nutrient absorption across the gut wall and can adversely increase fluid loss. It is therefore advised to offer a water-based ORS in between milk feeds, as without continuing to provide an adequate energy source from milk, the calf is at greater risk of LW loss, further dehydration and prolonged recovery (Nouri and Constable, 2006; Bachmann *et al.*, 2009; Wenge-Dangschat *et al.*, 2020). ORS are suitable for calves without an impaired suck reflex, however calves which are unable to suckle may require ORS via intravenous fluid therapy (Berchtold, 1999). Non-steroidal anti-inflammatories (NSAID) can be administered for pain relief and antibiotics if the source can be identified as bacterial (Todd *et al.*, 2010; Potter *et al.*, 2012). However, accurate identification is difficult based on visual diagnosis alone and

often further analysis is required for effective use of antibiotics as well as to reduce antimicrobial resistance.

Antimicrobials are used in the dairy industry to promote gut health and lower the risk of enteric infections (Smith, 2015), and are usually successful when administered subcutaneously in calves. In calf studies, antimicrobials have been found to alter the faecal microbiota of pre-weaned calves (Oultram *et al.*, 2015; Van Vleck Pereira *et al.*, 2016). Periera *et al.* (2016) found that the relative abundance of *Clostridium* and *Streptococcus* decreased when calves were fed milk that contained antimicrobials, suggesting that antimicrobials cause gut dysbiosis.

Probiotics are a popular alternative to antimicrobials to rebalance the calf's gut microbiome and adding probiotics to either calf milk replacer or starter concentrate can lower scour incidence (Quigley III *et al.*, 2002). Probiotics are active microorganisms that, when fed, help improve digestion, calf performance and building of the immune system (Frizzo *et al.*, 2011; Cangiano *et al.*, 2020). They do this by producing antibacterial compounds, such as acids and bacteriocins (antibiotic-like substances), which out-compete pathogenic bacteria and strengthen the GIT (Maldonado *et al.*, 2012). Prebiotics (Raza *et al.*, 2022), phytogenic substances (Sánchez *et al.*, 2021), and essential oils (Katsoulos *et al.*, 2017) have also been shown to improve gut health and immunity.

A recent meta-analysis identified 113 published literature on vaccinating dams or calves against GED (Maier *et al.*, 2022). Vaccine efficacy was variable against the most important causes of GED (predominantly rotavirus, coronavirus, and *Escherichia coli*), and more research was recommended for further studies on *Cryptosporidium*. Interestingly, Maier *et al.* (2022) found that vaccination may be a cover-up strategy to eliminate GED on farms with poor health management. The authors of a prospective cohort study in the meta-analysis found the risk of GED increased in calves with dams vaccinated against *Escherichia coli* (Bendali *et al.*, 1999). Therefore, Maier *et al.* (2022) suggest that vaccination should not be the only strategy to preventing GED and

health plans which include calves receiving adequate volumes of good quality colostrum are most successful.

Gut development

Research into the gut microbiota of dairy calves has become more advanced with development of next-generation sequencing, which has allowed researchers to produce a comprehensive profile of the early gut microbiota (Malmuthuge and Guan, 2017). Colonisation of the neonatal GIT is initiated during birth and occurs as an interaction between the host and microbiome, combined with various external factors (Van den Abbeele *et al.*, 2011). Host factors include luminal pH, gut retention time, and immune defence mechanisms; microbial factors include adhesion, survival mechanisms under oxygen gradient, and mechanisms to obtain nutrients from the host; and external factors include maternal microbiota, delivery mode, diet, and antibiotic treatment during early life (Penders *et al.*, 2006; Adlerberth and Wold, 2009).

The gut microbiota in fully developed ruminants is colonised by an intricate ecosystem of bacteria, archaea, protozoa, and fungi which enable the fermentation of complex carbohydrates and production of VFAs and microbial protein (Belanche *et al.*, 2021). However, the dominant bacterial species in the pre-ruminant differs to the adult rumen. Immediately following birth, GIT bacterial composition of individual neonates is largely heterogenous but becomes increasingly similar with age (Mayer *et al.*, 2012). Mayer *et al.* (2012) showed that the faecal microbial composition was more similar between twin calves than between siblings, implying that host genetics partly define individual gut microbial composition. From calf meconium samples, the authors identified *Actinobacteria* and *Bacteroidetes* as initial colonizers in the first 6 hours of life. *Actinobacteria* are gram-positive bacteria that can use carbohydrates to produce lactic acid, whereas *Bacteroidetes* generally produce butyrate and have antineoplastic properties which helps to maintain a healthy gut (Zhu *et al.*, 2021).

The aerobes, *Streptococcus* and *Enterococcus,* also colonise the GIT first and utilise available oxygen to create an anaerobic environment for strict

anaerobes, such as *Bifidobacterium* and *Bacteroides*, that have an important role in the development of the mucosal immune system (Malmuthuge *et al.*, 2015). The authors found by the second day of life, anaerobic bacteria dominate the GIT and the density of cellulolytic bacteria stabilises by the end of the first week. Between 8 and 10 days of life, anaerobic fungi and methanogens colonise the GIT, while protozoa only initialise after 15 days, and by 21 days of life, *Fecalibacterium* dominates the GIT along with *Bacteroidetes* (Malmuthuge *et al.*, 2015). *Faecalibacterium* is a butyrate-producing bacteria and promotes host health because it can inhibit the growth of pathogenic bacteria, such as *Escherichia coli* and *Salmonella (Oikonomou et al., 2013)*.

Microbial composition in the early rumen changes with age where the abundance of *Bacteroides* gradually replaces *Proteobacteria* (Figure 1.3). This age-dependent shift is thought to be due to introduction of dietary fibre (Malmuthuge *et al.*, 2015). The authors therefore encouraged to gradually incorporate solid feed to encourage rumen microbial growth since milk is bypassed into the abomasum.

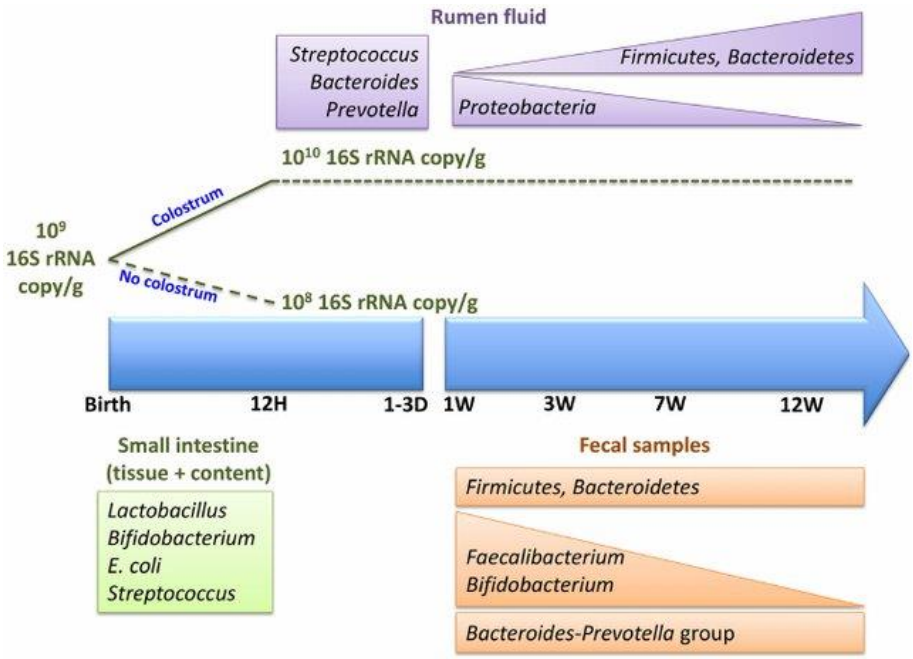


Figure 1.3: Colonisation of the neonatal calf gastrointestinal tract from birth to twelve weeks of life (Malmuthage *et al.*, 2015)

The role of the gut

The gut microbiome provides 70% of a ruminant's daily energy requirement via the fermentation of indigestible dietary substrates (Yeoman and White, 2014). A balanced gut microbiome will also support homeostatic development of the mucosal immune system (Hooper *et al.*, 2012), and dysbiosis in the gut microbiome has been linked to various enteric disorders that cause intestinal tissue inflammation in humans and mice.

A long-term increase in the population of Proteobacteria is indicative of an imbalance in the microbial community structure or presence of disease in the host (Spees *et al.*, 2013). Bennett and Eley (1976) have found that pH of the GIT is reduced in the presence of *Lactobacillus* because lactic acid which they produce inhibits growth and reproduction of pathogenic bacteria, such as *Escherichia coli*. Moreover, lactate can also be converted to butyrate, which maintains the environment's acidity and suppresses pathogenic growth. Oikonomou *et al.* (2013) suggested that the early gut microbial composition of calves might be linked to susceptibility to enteric infections, indicating that individual variations in early gut microbiota may play a role in the pathogenesis of GED. Stressors such as changes in diet, housing, weather, or weaning can upset the balance of the calf's gut environment, making the immune system unable to defend the body like it normally would (Osorio, 2020).

Malmuthuge *et al.* (2015) suggested that the first week of life is crucial for development of the gut wall. The gut wall is a barrier between the animal and the environment and 70% of a calf's immune system occurs at the gut level. The gut wall is involved with the development and function of the GIT such as the development of the intestinal epithelium, the mucosal layer (Sharma *et al.*, 1995), and lymphoid structures (Mebius, 2003) as well as the differentiation of immune cells. Physical barriers play a crucial role in preventing invasion of microbiota present in the intestinal lumen into intestinal tissue enriched with immune cells. The mucosal layer, the first physical barrier, contains secretory compounds (IgA, antimicrobial peptides) that trap and limit microbiota growth (Malmuthuge and Guan, 2017). For example, non-inflammatory IgA is secreted in response to commensal microbiota which binds to microbiota, preventing

microbiota entering the mucosal layer (Gutzeit *et al.*, 2014). Beneath the mucosal layer, a single layer of epithelial cells, connected by an intracellular junctional complex known as tight junctions (Ulluwishewa *et al.*, 2011), regulate the movement of macromolecules through the layer.

Gut microbiome and methane production

Although historically gut bacteria have been studied mainly to understand their modulatory roles in the mucosal immune system and in calf health (Malmuthuge *et al.*, 2012; Oikonomou *et al.*, 2013), recent studies on the intestinal archaeal community emphasize that in-depth understanding of this microbial group is useful in controlling enteric methane emissions. Rumen archaea produce methane as a metabolic by-product in hypoxic anaerobic conditions through three predominant pathways; by using hydrogen to reduce carbon dioxide or removing excess hydrogen from acetate or 1-carbon compounds, such as methanol, in an energy gaining process (Wilkinson, 2012). Like bacteria, archaea vary along the GIT (Zhou *et al.*, 2014) and the amount of methane they produce can be influenced by feed intake and diet composition. Nutritional studies in adult cows have investigated various dietary inventions, such as plant oil supplementation (Vargas *et al.*, 2020) and seaweed (Min *et al.*, 2021), which have the potential to reduce enteric methane production by 60%. Studies in calves are limited, however, calves which were given a daily oral treatment of methane inhibitor, 3-nitrooxypropanol, between birth and weaning (11 weeks of age), produced less VFA between weeks 1 and 49 post-weaning.

1.2.3.2 Bovine respiratory disease

BRD is a leading global hindrance to rearing replacement heifers in terms of prevalence and economic cost, reducing survival rates, growth, and future productivity. BRD is a general term to describe a range of complications that occur in the bovine respiratory tract, including upper respiratory infections and several varieties of pneumonia (Gaudino *et al.*, 2022). In the UK it is estimated that BRD affects almost 1.9 million cattle each year. The incidence risk of disease may range from 2 to 39% (Van Donkersgoed *et al.*, 1993; Gulliksen *et al.*, 2009a; Gulliksen *et al.*, 2009b), with up to 20% of calves presenting

respiratory disease before death and 37% showing lung pathology post-mortem (Statham, 2013). According to the 2007 US National Animal Health Monitoring Survey, the incidence of post-weaning respiratory disease in dairy heifers was 6% and was responsible for almost half (47%) of reported heifer deaths.

Aetiology

Like GED, BRD is best defined as multifactorial, with several risk factors including environmental, nutritional, and social changes, such as increased exposure to pathogens when first introduced to older animals (Taylor *et al.*, 2010). Numerous bacterial species can be isolated from the lungs of infected cattle, however the leading causes of respiratory disease outbreaks in younger animals are *Mannheimia haemolytica*, *Pasteurella multocida*, *Histophilus somni* and *Mycoplasma bovis*. These pathogens are usually described as ubiquitous in cattle populations as they are easily identifiable in the nasopharynx of a proportion of animals in nearly all herds (Callan and Garry, 2002). The authors identified several prevalent viral causative agents include bovine viral diarrhoea virus, bovine respiratory syncytial virus, and parainfluenza type 3 virus. Bacterial colonisation establishes after preliminary infection from viral aetiologies and environmental stressors, which impair resistance mechanisms in the lungs and propagate disease progression (Taylor *et al.*, 2010).

Diagnosis and treatment

BRD is typically diagnosed upon observation of clinical symptoms such as droopy ears, a snotty nose, elevated temperature, drawn-out and coughing (Cramer *et al.*, 2019). Severity of symptoms can be scored according to a standardised system (McGuirk and Peek, 2014) and new research is investigating the use of thoracic ultrasound for more accurate and rapid diagnosis of early or sub-clinical respiratory disease (Buczinski *et al.*, 2013; Ollivett and Buczinski, 2016). Additionally, automatic calf feeders (ACF) may indicate ill health through changes in recorded feed intake and behaviour. For example, Borderas *et al.* (2009b) found that calves fed an elevated level of milk (>8 L/d) had a lower milk intake on the same day that they were detected as sick by a trained human observer. In another study, Svensson and Jensen

(2007) reported that sick calves had a reduction in the number of visits to the ACF without a milk meal. The use of ACF for early detection of disease is gaining research popularity (Svensson and Jensen, 2007; Swartz *et al.*, 2017; Cramer *et al.*, 2020).

A recent review studying effectiveness of several BRD antimicrobials found the observed risk ratio of retreatment was 0.54 and was similar for florfenicol, tulathromycin, enrofloxacin, and danofloxacin (O'Connor *et al.*, 2016). However, antimicrobial treatment for BRD did not affect growth in heifers with a history of BRD suggesting that treatment does not compensate for earlier disease incidence (Stanton *et al.*, 2012). This is likely to be because the health and performance of the infected heifer have already been affected by BRD. Metaphylactic use of antibiotics at weaning has been shown to reduce the incidence of BRD (Van Donkersgoed *et al.*, 1993), however this is not encouraged due to increasing the risk of antimicrobial resistance. Therefore, animals with clinical symptoms of respiratory disease should be treated on an individual basis (DeDonder and Apley, 2015). NSAIDs are also commonly used alongside antibiotics and may reduce rectal temperature and lung damage on BRD-affected animals, but evidence of this lacks reliability (Francoz *et al.*, 2012) and more research is needed to determine the short and long term effects of NSAID treatment on health and performance.

Various univalent and multivalent vaccinations against viral and bacterial causative agents of BRD in cattle have been investigated with mixed efficacy (Robb *et al.*, 2007; Makoschey *et al.*, 2008; Vangeel *et al.*, 2009; Teixeira *et al.*, 2017b). The use of modified live virus vaccines has been shown successful in reducing the shedding of respiratory viruses and incidence of clinical disease (Xue *et al.*, 2010). However, the effectiveness of vaccinating against bacterial sources is less clear (Aubry *et al.*, 2001). This may be due to the timing of the vaccination, for example, symptoms are usually observed following initial movement to group housing and/or at weaning (McGuirk, 2008), therefore calves must be vaccinated with sufficient time prior to this to ensure adequate immunity development. Other factors include lack of booster doses and attention to the primary causative risk factors (Stokka, 2010). However, other

studies have shown that vaccinated cattle have greater DLWG (Schunicht *et al.*, 2003; AFBI, 2015), but vaccination was not always associated with growth rate (Frankena *et al.*, 1994). Nevertheless, vaccinating should not compensate for other preventative measures such as good quality colostrum and appropriate ventilation which are highly recommended (Gorden and Plummer, 2010).

1.2.3.3 Effect of calf-hood disease

Impact on costs

Calf-hood diseases have a major impact on economic viability of cattle operations, due to direct costs of calf losses and treatment and long term effects on performance. The UK cattle industry loses £11 million annually to GED (Bennett and IJpelaar, 2005) and £60 million to respiratory diseases; between £30 for mild cases and £500 when the animal dies (AHDB, 2013). Of these costs, only 40% accounts for veterinary treatment with the remaining hidden costs, such as lower DLWG through reduced FCE. The large potential economic losses suggest a complete understanding is required of its effects on heifer development and lifetime performance. The long-term costs of calf-hood disease are likely underestimated due to poor disease recording for heifers, which makes it difficult for producers to associate calf-hood disease with long-term negative outcomes. Studies have documented long-term costs of calf-hood diseases, including higher incidence of mortality before calving (Waltner-Toews *et al.*, 1986b); decreased growth (Virtala *et al.*, 1996b); later AFC (Waltner-Toews *et al.*, 1986b; Correa *et al.*, 1988; Correa *et al.*, 2013), and greater risk of dystocia (Warnick *et al.*, 1994).

Growth rate and heifer development

Several studies confirm a reduced growth rate due to increased incidence of disease during the rearing period. Differences in DLWG usually emulate the environmental conditions the calf experiences as well as health challenges such as GED and BRD (Bruning-Fann and Kaneene, 1992). Huge variations in rates at the early stages of growth have been associated with season of birth and occurrence of scour, septicaemia, and respiratory disease (Heinrichs and

Heinrichs, 2011). Depression in appetite from scour in neonates can considerably reduce early growth, as well as weaken resistance to subsequent disease. Calves that survived scour before 14 days of life were more susceptible to respiratory tract infections in the ensuing period (Curtis *et al.*, 1988; Virtala *et al.*, 1999; van der Fels-Klerx *et al.*, 2001). Olson *et al.* (2004) associated malabsorptive diarrhoea with decreased DLWG as did Donovan *et al.* (1998a, 1998b) who found calves treated for as few as three days for scour between 0 and 416 days (0 and 14 months) had an extended growth period of 13 days. In the study by Donovan *et al.* (1998a), the DLWG between 183 and 426 days (6 and 14 months) was decreased by 0.02 kg/d when the number of days treated for BRD before 183 days (6 months) increased (Donovan *et al.*, 1998b). Stanton *et al.* (2012) found a 14.3 ± 2.1 kg decrease in LW in calves treated for BRD at approximately 395 days (13 months) of age due to such differences in DLWG. Respiratory disease in beef feedlots is associated with decreased DLWG, marbling, meat quality, subcutaneous fat cover and increased mortality (Smith, 1998; Reinhardt *et al.*, 2009; Schneider *et al.*, 2009). Lastly, Brickell *et al.* (2009b) showed that mortality to 183 days (6 months) was higher in calves whose LW was low at 30 days and that herds achieving lower mean growth rates to 61 days (2 months) had higher mean AFC and more variation in AFC.

Age at first calving

Many studies have reported a relationship between calf-hood disease and AFC. Heinrichs *et al.* (2005) investigated the factors between calf health and AFC on 18 farms and identified number of days treated with antibiotics as a significant factor. Other factors included inadequate housing conditions such as higher humidity, mean daily temperature and ammonia levels (Heinrichs *et al.*, 2005). However, the delay in AFC due to disease during the rearing period is inconsistent. Some studies report the difference in months, for example, Correa *et al.* (1988) found that heifers which had BRD in the first 91 days (3 months) of life calved 6 months later than heifers without BRD, whilst Warnick *et al.* (1994) reported a 3 months delay. Whereas others report the difference in days, for example, Bach (2011) found that heifers which had four or more BRD cases

calved 8 days after heifers which had no cases (732 ± 3 days and 724 ± 2 days, respectively), whilst Stanton *et al.* (2012) reported a 12 day delay in BRD-infected heifers and were half as likely to calve before 760 days (25 months) than heifers without BRD. On the other hand, Waltner-Toews *et al.* (1986c) found no effect of BRD on the probability of calving by 900 days (30 months) of age, however heifers treated for scour within the first 91 days (3 months) of life were nearly three times more likely to calve after 900 days (30 months) of age than heifers not requiring treatment (Waltner-Toews *et al.*, 1986b).

Milk production and fertility

Few studies have investigated long-term impacts of calf-hood disease, but of these studies many report no difference in milk production between heifers with and without a history of ill health (Britney *et al.*, 1984; Warnick, 1995; Teixeira *et al.*, 2017a; Hurst *et al.*, 2022). Heinrichs and Heinrichs (2011) found number of days which Holstein heifers spent coughing or scouring before 122 days (4 months) of age reduced first lactation milk yield but was not associated with lifetime production. Likewise, there was no difference between heifers with and without a history of BRD on 305-d mature equivalent milk production, but heifers with scour produced 325 kg less in first lactation (Abuelo *et al.*, 2021). Similarly, Svensson and Hultgren (2008) found heifers that had scour before weaning (3 months of age) had a lower first lactation yield. Therefore, the negative effect reported by Heinrichs and Heinrichs (2011) could be due to assessing BRD and scour concurrently. Nevertheless, some studies have found that BRD in early life reduces first lactation milk yield. For example, an American study using 14,000 Holstein heifers from one farm found that BRD before 120 days of age reduced first lactation milk yield by 233 kg (Schaffer *et al.*, 2016). Similarly, a large meta-analysis using European studies reporting BRD cases in heifers from birth to 12 months (365 days) of age, observed a 121 kg decrease in first lactation milk yield (Buczinski *et al.*, 2021). Additionally, Soberon *et al.* (2012) found that for every 1 kg of pre-weaning DLWG, calves treated with antibiotics produced 784 kg less milk than calves that did not receive antibiotics. The disparities in the results of these studies indicate further research is needed to determine the association between early calf health and milk production. Lastly,

severe BRD in Swedish Red calves during their first 183 days (6 months) increased calving interval by 12% in mature cows, while calves contracting scour over this period produced significantly less milk in their first 305-day lactation (Svensson and Hultgren, 2008; Hultgren and Svensson, 2010).

Longevity

An evaluation of management practices for pre-weaned dairy heifer calves in the US found that 38% of calves had at least one morbidity event during the pre-weaning period (Urie *et al.*, 2018), which is higher than the target 25% morbidity rate for pre-weaned calves (USDA, 2010).

Previous studies investigating the impact of calf health in early life found that incidence of calfhood disease negatively impacted survival. Bach (2011) found that heifers which had 4 or more cases of BRD were 1.9 ± 0.1 times less likely to survive first lactation compared with heifers that had no BRD cases. This is consistent with Walter-Toews *et al.* (1986b) who found that heifers treated for BRD in the first 90 days of life were 2.5 times more likely to die between 90 days of age and first calving. This increased risk might, on the one hand, be because tissue function and immunity are reduced after initial infection. This supports other studies which found that heifers treated for scour are more susceptible to respiratory tract infections in the ensuing period (Curtis *et al.*, 1985; Virtala *et al.*, 1999; van der Fels-Klerx *et al.*, 2001). On the other hand, concurrent early BRD and later mortality could indicate poor genetic merit and/or immunological vigour in these heifers. Similarly, Stanton *et al.* (2012) found heifers with BRD were 1.7 to 3.4 times more likely to be removed from the herd before first calving but did not affect survival to 120 DIM in heifers that survived calving. This could be due to many factors, including prior selection for healthy animals, such that by the time animals have calved, the most severely affected animals had been removed from the herd. Consequently, the impact of BRD on dystocia, milk production, and post-calving survival may also be underestimated and further culling may occur after 120 DIM which needs to be considered. The authors suggest that culling represents a survival bias and is a common challenge in long-term studies of diseases. Ideally, studies should be extended to include lactation production records as endpoints to assess the

long-term economic effects of calf diseases more accurately (Waltner-Toews *et al.*, 1986a).

The results of Curtis *et al.* (1988) differ from the aforementioned studies as BRD was not associated with survival to calving. This may be due to the severity of the disease events considered. Curtis *et al.* (1988) included any BRD event regardless of treatment, whereas other studies may have included only calves that were ill enough to be treated.

1.2.3.4 Prevention

Failure of passive transfer

Calves are born with no immunity derived maternal antibodies, so initially rely on the transfer of protective immunoglobulins in colostrum (Stott and Fellah, 1983; Weaver *et al.*, 2000; Godden *et al.*, 2019). Inadequate intestinal absorption of colostral immunoglobulins within the first 24 hrs of life leads to failure of passive transfer (FPT) of immunity, which is defined as serum IgG levels of less than 10 mg/mL (Beam *et al.*, 2009). The association between passive transfer of colostral immunoglobulins and subsequent health status in the calf has been well documented (Boyd, 1972; Boyd *et al.*, 1974; Braun and Tennant, 1983). Negative outcomes associated with FPT include increased pre-weaning morbidity (Donovan *et al.*, 1998a) and mortality (Robison *et al.*, 1988), increased duration of illness (Pare *et al.*, 1993), increased contagiousness or pathogen shedding (Lopez *et al.*, 1988), reduced growth (Dewell *et al.*, 2006), and increased culling rates (DeNise *et al.*, 1989).

There is also wide variation in efficiency of lactoglobulin absorption, with up to 30% of calves remaining hypogammaglobulinemic during their first 24 hrs when fed the same colostrum program (Klaus *et al.*, 1969). The incidence and severity of disease were lowest in heifer calves with serum Ig levels greater than 10 g/L at 30 to 60 hrs of life (Furman-Fratczak *et al.*, 2011). These calves did not become ill before 14 days of life and reached mating LW sooner, allowing for an earlier first service. Additionally, calves with serum γ-globulin greater than 15 g/L did not contract respiratory disease (Furman-Fratczak *et al.*, 2011). In another study, pre-pubertal DLWG up to 180 days (5.9 months) of

age was positively correlated with serum Ig concentrations during the first 7 days of life (Robison *et al.*, 1988). Other studies found no relationship between colostrum feeding, growth, and health status in dairy beef calves (Barber, 1978; Fallon, 1978; Caldow *et al.*, 1988). In a study in which an association between good colostrum management and heifer growth was found, no effort was made to determine if the effect was directly due to colostral-derived immunoglobulins or other colostral compounds, or if the effect was mediated through a reduction in disease incidence or severity (Donovan *et al.*, 1998a). Lastly, a high level of colostral immunoglobulins in the serum of calves improves not only their health and growth in the first weeks of life but continues into adulthood (DeNise *et al.*, 1989; Donovan *et al.*, 1998a; Jarmuz *et al.*, 2001).

Stress can reduce immunoglobulin absorption as corticosteroids render the small intestine's permeability of absorbing macromolecules including immunoglobulins (Husband *et al.*, 1972; Stott, 1980). Therefore, minimising physiological stress with ambient environmental conditions, including the absence of pain and fear which raise adrenal steroids, is critical for survival especially in the first 24 h after birth. Calves exposed to heat stress have been found to have elevated body temperatures, higher serum corticosteroids in serum, lower serum IgG1 concentrations, and higher mortality rates (Stott *et al.*, 1976).

Lastly, Godden (2008) reported that calves born to primiparous cows were more susceptible to FPT than those with multiparous dams. This is because older cows have greater exposure to more farm-specific pathogens which potentially increases their concentration of IgG. Dam parity and birth weight were positively correlated; however birth weight was negatively correlated with IgG concentration, which could explain why calves from first lactation cows had the highest IgG concentrations despite contradicting effect of lactation on colostrum quality (Shivley *et al.*, 2018).

Housing

Studies have shown a significant association between dairy housing and BRD incidence. Radostits *et al.* (1994) found older calves and mature animals in a

herd are a source of infection, therefore they should not share air spaces with younger calves. A higher transmission rate of BRD is observed in grouped calves due to contributing factors such as number of animals, animal density, housing facilities, humidity, and ventilation (Gorden and Plummer, 2010). Housing calves in hutches has been demonstrated to improve calf health (Quigley *et al.*, 1994b). Individual hutches, correctly spaced 4m apart, effectively reduces aerosol transmission of respiratory microbes (Mars *et al.*, 2000). A Minnesota study reported that housing calves individually affected growth rate no differently than immediately grouping calves post-weaning (Ziegler *et al.*, 2008). However, Bach *et al.* (2010) found increased growth rates and fewer respiratory treatment in calves weaned and grouped at 49 days, compared with calves housed in separate hutches for 7 days (BRD incidence = 20% and 34% respectively). Other research has shown that housing computer-fed calves in groups of 10 or less, improves growth and reduces BRD-related morbidity (Svensson and Liberg, 2006). Solid dividers between individually housed calves are effective in reducing BRD by decreasing pathogenic exchange between pens and preventing direct nose-to-nose contact (Lago *et al.*, 2006). Greater nesting scores are associated with straw bedding and are related with reduced BRD incidence (Lago *et al.*, 2006). The ability to nest decreases the calf's lower critical temperature, eliminating the additional caloric requirement for cold environments.

Ventilation

Inadequate ventilation is detrimental to respiratory health and is therefore a critical aspect of heifer management. Most viral and bacterial respiratory pathogens can transmit aerogenously and reach high concentrations in poorly ventilated areas (Lago *et al.*, 2006; Cobb *et al.*, 2014; Roland *et al.*, 2016a). Poor air quality is typically labelled the largest risk factor for BRD in dairy calves at herd level (Pritchard *et al.*, 1981; Lago *et al.*, 2006), with filtered air, containing low bacterial and dust concentrations, associated with decreased incidence of BRD (Pritchard *et al.*, 1981; Hillman *et al.*, 1992). Other environmental factors contributing to increased pathogenic density and exposure in housed calves include relative humidity levels greater than 75%,

rapidly changing environmental temperatures, extreme heat or cold, and high concentrations of noxious gases, such as ammonia, that adversely affects pulmonary function. Proper ventilation will effectively minimise these factors. Airborne pathogen exposure can be increased by overcrowding and subsequently exaggerate animal stress and reduce immune responsiveness. It is important that correct ventilation flows from younger to older cattle to reduce pathogenic transmission to more vulnerable animals as calves are at increased pathogenic exposure when in contact with older animals or sharing air space (Callan and Garry, 2002). The authors advised housing systems should be designed to reduce these risk factors associated with poor ventilation and respiratory disease development.

1.2.4 Fertility

1.2.4.1 Attainment of puberty

The age at which heifers attain puberty is an important production trait of good lifetime productivity in both dairy and beef cattle production systems (Patterson *et al.*, 1992; Sejrsen and Purup, 1997). Puberty is reached when a heifer ovulates a potential fertile oocyte which may be accompanied by visual signs of oestrus (Perry, 2012). However, in reality ovulation and oestrus are often two separate events and up to 25% of animals can show oestrus without ovulating (Nelsen *et al.*, 1985; Byerley *et al.*, 1987). More commonly first ovulation is accompanied by a short luteal phase and a subsequent decrease in progesterone which stimulates first behavioural changes (Gasser, 2013).

Dairy systems which aim to calve heifers at 730 days (24 months) should reach puberty by 365 days (12 months) of age to allow a few cycles before starting to mate (Wathes *et al.*, 2014). In Holstein-Friesian heifers, onset of puberty usually occurs around 274 days of age (Davis Rincker *et al.*, 2011b) with 274 kg of LW (Capuco *et al.*, 1995; Macdonald *et al.*, 2007), but literature means range between 250 days (Bruinjé *et al.*, 2021) and 335 days (11 months) (Capuco *et al.*, 1995; Lammers *et al.*, 1999; Macdonald *et al.*, 2007) with a LW of 247 kg (Bruinjé *et al.*, 2021) to 309 kg (Lammers *et al.*, 1999; Davis Rincker *et al.*, 2011b). However, both age and LW at onset of puberty vary widely within, as

well as between, breeds and in studies using Friesian and Danish Red heifers, onset of puberty ranged from 152 to 608 days (5 to 20 months) of age and between 150 to 400 kg (Foldager *et al.*, 1988). Although fewer than 5% attained puberty at less than 200 kg and less than 10% greater than 300 kg. Additionally, in a study using progesterone measurements to confirm ovulation, heifers ovulated on average at 289 days (9.5 months), but ranged from 228 to 411 days (7.5 to 13.5 months) (Taylor, 2001).

Onset of puberty is more correctly achieved at a proportion of MW (Freetly *et al.*, 2001), between 38% (Sejrsen and Purup, 1997) and 43% MW (Van Amburgh *et al.*, 1998) rather than age, as puberty is influenced by body fat percentage (Mourits *et al.*, 1997; Abeni *et al.*, 2000) and nutritional status (Schillo, 1992). Adequate level of nutrition is required for the proper functioning of the endocrine system since nutrition influences synthesis and release of the hormones necessary for attaining sufficient LW and sound fertility. Normally the amount of body fat rises as puberty approaches which is associated with increased leptin concentrations (Zieba *et al.*, 2005). This could be part of the metabolic signalling necessary for attainment of puberty (Cunningham *et al.*, 1999). Circulating concentration of insulin-like growth factor 1 (IGF-1) is highly correlated to LW and DLWG during the period of pre-pubertal growth (Lammers *et al.*, 1999; Brickell *et al.*, 2009b). Velasquez *et al.* (2008) found changes in IGF-1 concentrations before puberty were strongly influenced by nutritional status and were reduced by dietary restrictions, which also delayed puberty.

Greater pre-pubertal DLWG has an accelerating effect on attaining puberty (Le Cozler *et al.*, 2008). Diets higher in energy and protein have been shown to increase DLWG and lower age at puberty and AFC (Lammers *et al.*, 1999; Davis Rincker *et al.*, 2011a; Froidmont *et al.*, 2013). Shamay *et al.* (2005) compared feeding unrestricted whole milk with 0.45 kg/ DM of milk replacer and concluded that ad libitum milk, followed by a post-weaning ration supplemented with an additional 2% CP of fish meal protein, increased DLWG to 0.88 kg/d during the pre-pubertal period and decreased age of puberty by 23 days. Rincker *et al.* (2011) bred heifers fed either a conventional or intensified diet at the same LW without considering age as a factor. Thus, LW was not different

at conception, but heifers fed increased levels energy and protein attained puberty 30 days earlier and conceived 15 days earlier than heifers fed conventional energy and protein levels. Similarly, Macdonald *et al*. (2005) found Holstein-Friesian heifers grazed to achieve a growth rate of either 0.4 kg/d, 0.6 kg/d or 0.8 kg/d, all attained puberty at the same LW (251 ± 25 kg), however, heifers achieving the highest growth were 36 days and 64 days younger than heifers achieving the two lower growth rates, respectively.

1.2.4.2 Age at first service

A dairy producer exercises control over heifer rearing in two main areas: nutritional plane of growth and age at first service (AFS). These two management factors interact with biological aspects of growth, thereby influencing future profitability of the dairy heifer (Hoffman and Funk, 1992). The decision to start insemination is often based on age, and size may only be considered for heifers that are small for their age (Storli *et al.*, 2017). In a survey of Dutch dairy farms, 60% of farms used age and not LW to determine first service (Mohd Nor *et al.*, 2013). The minimum age at which farmers said they were willing to start serving their heifers was 453 days (14.9 months), ranging from 395 to 548 days (13 to 18 months), but the actual mean value was 30 days later at 484 days (15.9 months). Holstein-Friesians are considered a later maturing and heavier dairy breed (Handcock *et al.*, 2018) and according to the NRC (2001), first service can occur when 55% MW is reached. However, variability in growth rates within the same group of heifers can lead to a large spread in the age at which they are first served (Ettema and Santos, 2004; Brickell *et al.*, 2009c). Nevertheless, using 55% MW as a target, Pietersma *et al.* (2006) reached optimal pre-mating LW at 414 ± 43 days (13.6 ± 1.4 months) in Canadian Holstein heifers and 90% of heifers attained sufficient maturity by 456 days (15 months) of age, suggesting calving Holstein heifers at 24 months is realistic. However, in a report using 20 dairy farms in Southwest England, 78% of Holstein-Friesian heifers reached the pre-mating LW target of 374 kg at the start of the service period (420 days of age) (Bazeley *et al.*, 2016). The LW target was calculated as the expected 75th percentile LW at 420 days using mean DLWG across all farms of 0.70 kg/d. This meant that heifers on farms

with lower DLWG were expected to weigh 302 kg at start of service, and fewer than 10% of heifers in these farms reached pre-mating targets. These results indicate that a universal target may not be suitable for all farms.

Feeding diets for higher DLWG enables heifers to achieve pre-mating LW earlier, potentially decreasing age at calving and costs associated with raising replacement heifers (Radcliff *et al.*, 1997; Raeth-Knight *et al.*, 2009). Increasing DLWG from 0.68 to 0.82 kg/d between birth to conception reduced age at conception by 32 days (Bar-Peled *et al.*, 1997). Moreover, reducing AFS decreases AFC and the number of non-productive days which can offset higher feed costs during the rearing period (Boulton *et al.*, 2015).

1.2.4.3 Management and techniques

The way that heifer fertility is managed and achieved can vary considerably between farms. Typically, artificial insemination (AI) may be used initially and perhaps for a set number of serves, and then a sweeper bull is run with any non-pregnant animals. Running heifers with a bull can be easier and cheaper than AI, costing £32.31 per heifer (Boulton *et al.*, 2015), but there is a tendency to start serving heifers later with this strategy, so age at conception can be up to 548 days (18 months). This increases AFC and overall rearing costs. Use of sexed semen has become more popular over recent years due to increased welfare and financial implications concerning undesirable bull calves on dairy units. Conventional and sexed semen costs £15 and £30 per straw respectively and have been found to have conception rates of 66% and 60% respectively, however, ranges were twice as variable with convention semen (50% and 21% respectively) (Boulton *et al.*, 2015). This supports other larger studies that found AI success were 20 to 30% lower in sexed semen compared to unsexed (McCullock *et al.*, 2013; Seidel, 2013). Sexed semen can increase rearing costs significantly by around £30 to £70 per animal dependent on the strategy used (Boulton *et al.*, 2015) but were found to have minimal effect on profitability since dairy heifers have greater value than dairy bulls so this additional expense can be recouped later (McCullock *et al.*, 2013). Additionally sexed semen has also been shown to reduce dystocia at first calving and has enabled faster genetic progress by increasing the number of dairy heifers born into the herd

(Schuenemann *et al.*, 2011). Therefore, it was more important to assess on-farm management and the relative value of heifer, bull and beef calves when considering using sexed semen.

1.2.4.4 Conception rate

Genetic merit for reproductive efficiency has declined over recent decades due to selection for milk (Tsuruta *et al.*, 2005). Conception rates (CR) were around 60% in the 1970s for UK herds and decreased to 40% in the 1990s (Royal *et al.*, 2000), and to 35% in 2019 (Hanks and Kossaibati, 2019). Furthermore, poor CR increases variability in AFC, even when nutrition and DLWG are adequate to meet mating targets (Ettema and Santos, 2004). In the UK, overall first service CR in heifers was found to be 67% in heifers (Brickell *et al.*, 2009a) but fertility deteriorated with age (Boulton *et al.*, 2015). Kuhn *et al.* (2006) found heifers first bred between 395 and 487 days (13 and 16 months) had a higher CR of 56% compared to 42% in heifers bred between 791 and 821 days (26 and 27 months). Therefore, close monitoring of oestrus behaviour and ease of handling is important, particularly when using AI. Additional handling before first service lowered cortisol levels and time to puberty which is important in excitable or aggressive heifers which have been found to have lower CR (Cooke *et al.*, 2012). Heat detection tools to support oestrous behaviour are beneficial, especially in animals with short oestrus cycles, as sole visual observation has been found to miss 37% of animals in heat when compared with radio telemetric recording (Stevenson *et al.*, 1996). However, Byerley *et al.* (1987) found that pregnancy rates increased from 57% to 78% between the first and third observed oestrus in beef heifers. This was thought to be because the reproductive tract continues to develop post-pubertally under the influence of alternating peaks of oestradiol and progesterone.

1.2.4.5 Calving problems

Poor fertility will increase AFC while abortion in late gestation can reduce AFC if animals are sufficiently far advanced to lactate. Bach (2011) found that 4.8% of 7768 Holstein heifers aborted and were rebred with an AFC ranging from 662 to 1048 days (21.8 to 34.5 months). These animals were 2.7 times more likely

to leave the herd without completing the first lactation and one-third of these were culled or died within 50 days from calving. Inadequate skeletal maturity can be a problem if AFC is earlier than 730 days (24 months) (Hansen *et al.*, 2004). On the other hand, Simerl *et al.* (1991) and Bach (2011) both reported that AFC could be reduced to 669 days (22 months) without an increased frequency of problems at parturition. At the other extreme, over-conditioned heifers are also at greater risk of calving problems and is more likely to occur in heifers with delayed first service or poor fertility (Cooke *et al.*, 2013).

1.3 Factors affecting milk yield

Numerous factors influence the milk yield of a dairy cow, such as her genetics, biological and physiological aspects, diet, and environmental and management considerations. However, in terms of AFC and WFFE, this review will focus on growth rate, LWFC and dry matter intake (DMI).

1.3.1 Growth rate

The effect of growth rate throughout the rearing period has been widely researched due to its close association with mammary development and future milk production.

1.3.1.1 Mammary development

Studies report reduced mammary development when feeding heifers for high growth rate during the critical period. These studies appear to be based on the underlying assumption proposed 40 years ago that pre-puberty is the “critical period” during which mammary development is sensitive to feeding level (Sejrsen *et al.*, 1982b). This is because mammary development undergoes three distinct growth phases; between approximately 56 and 274 days (1.8 and 9 months) of age, mammary growth is allometric (develops up to three times faster relative to overall body growth) (Desjardins and Hafs, 1969); then it becomes isometric after puberty; followed by a second allometric phase after mating (Sinha and Mohan, 1969).

Studies have reported that high DLWG leads to greater mammary epithelium, which is the main factor limiting milk production (Brown *et al.*, 2005). Before 56 days (1.8 months) of age only non-epithelial tissue, such as the stroma and circulatory system, develops, and then from 56 days (1.8 months), the fat pad and glandular ducts develop rapidly. The basic structures of the mammary glands are formed in foetal life, but epithelial tissue is still undeveloped at birth. Mammary epithelium growth is influenced by rate of epithelial cell proliferation and apoptosis (Capuco *et al.*, 2003), cell differentiation status and secretory activity of myoepithelial cells (Akers, 2006). Meyer *et al.* (2006) found that increasing DLWG from 0.65 to 0.95 kg/d between 10 and 60 days of age increased proliferation of mammary gland epithelium by 40%. Likewise, Brown *et al.* (2005) found increasing protein and energy intake in milk replacer between 14 and 56 days of age almost doubled the amount of mammary parenchymal DNA and increased the amount of mammary parenchymal tissue at weaning. Hence why the first allometric phase between birth and weaning from milk to puberty has been found most important for mammary development (Margerison *et al.*, 2013).

1.3.1.2 Pre-pubertal growth rate

The concern with feeding high-energy diets and rapid growth rate is producing over-conditioned heifers with excessive mammary adipose tissue and parenchyma, resulting in decreased milk yield potential (Sejrsen *et al.*, 1982a; Foldager and Sejrsen, 1987; Radcliff *et al.*, 1997). Hoffman and Funk (1992) reasoned that the high energy demand in rapidly reared heifers to achieve earlier puberty, accelerates body growth at the expense of mammary development. Meyer *et al.* (2004) supports this reasoning as, although there was no difference in daily mammary parenchymal growth between heifers with 0.65 and 0.95 kg/d DLWG, puberty was attained sooner in heifers grown at a higher rate which resulted in lower total parenchyma and reduced milk yield. Previous studies agreed that DLWG above 0.9 kg/d in the pre-pubertal period will impair mammary development and decrease first lactation milk yield (Sejrsen *et al.*, 1982a; Lammers *et al.*, 1999; Sejrsen *et al.*, 2000), with one study finding a 5% reduction in 305-d lactation yield when DLWG was exceeded

(Van Amburgh *et al.*, 1998). However, Macdonald *et al.* (2005) indicated that any negative effect of accelerated growth before puberty on milk yield may be offset by a higher LWFC (Macdonald *et al.*, 2005). Therefore, it was generally recommended that growth should be carefully managed between 0.75 to 0.85 kg/d during the critical period (Margerison and Downey, 2005; Cooke and Wathes, 2014).

Soberon *et al.* (2012) found pre-weaning DLWG accounted for 22% of variation in first lactation milk yield, suggesting that faster growth rate before weaning may be associated with epigenetic programming that results in higher milk yield, but this mechanism is not yet fully understood. In their study, heifers yielded 850 kg more milk in their first lactation for every 1kg of DLWG before weaning and 56 kg more milk for every MJ of metabolisable energy intake above maintenance. Likewise, Chuck *et al.* (2018) found that events in the pre-pubertal period (85 to 473 days of age) had the greatest effect on first lactation milk yield and for every 0.1 kg/d increase in pre-pubertal DLWG, heifers produced an additional 182 L at 100 DIM and 345 L at 250 DIM.

Other studies have found that DLWG from solid feed has a significant positive effect on first lactation milk yield. Bach (2012) found that dairy heifers produced 225 kg more milk in their first lactation for every 0.1 kg/d increase in DLWG from solid feed in their first 8 weeks of life. This is similar to Chester-Jones et al. (2017) who found every 1 kg of calf starter DMI at 56 days of age, first lactation yield was increased by 8.2 kg. Likewise, Holstein heifers with a 1 kg increase in weaning DMI produced 287 kg more milk in first lactation (Heinrichs and Heinrichs, 2011). The authors thought this may be related to body size at weaning or feeding management, resulting in a greater LWFC, however, it did not show in previous analyses as a factor affecting age or size at first calving (Heinrichs *et al.*, 2005). Additionally, this positive relationship was only found in pre-weaning DLWG between 0.5 and 0.9 kg/d and the effect on first lactation performance outside of this range was minimal. When considering effects of milk intake on first lactation performance, for every 100 g/d of milk DMI, first lactation milk yield increased by 66 kg (Gelsinger *et al.*, 2016). This increased to 139 kg when combined with solid feed DMI. Similarly, in terms of the milk-

feeding period, both Shamay *et al.* (2005) and Moallem *et al.* (2010) found that heifers fed whole milk and supplemented with an additional 2% protein after weaning, produced more milk in their first lactation compared to heifers fed milk replacer or with no protein supplementation. Lastly, although there is limited research on the effect of birth weight on milk yield, a study using Iranian Holstein calves found birth weight was positively associated with first lactation milk yield (Ghoraishy and Rokouei, 2013). The current consensus, therefore, supports the view that providing heifers with a good start in life through better nutrition will benefit their later milk production potential.

Some recent studies have reported no or minimal effect of feeding for greater DLWG to achieve higher milk yield. Gelsinger *et al.* (2016) concluded that pre-weaning DLWG accounted for less than 3% of variation in first-lactation milk yield and that other factors were more important. Additionally, based on earlier findings that heifers achieving higher pre-weaning DLWG had greater mammary growth (Brown *et al.*, 2005), Rincker (2011) hypothesised that heifers consuming more milk will grow faster and have a greater first lactation milk yield. However, there was no difference in first lactation milk yield between heifers fed milk intensively or conventionally, despite heifers offered more milk growing faster before weaning. Van Amburgh *et al.* (1998) reported a reduction in fat-corrected milk (FCM) yield in heifers grown at 0.94 versus 0.68 kg/d but found that pre-pubertal rate of gain only explained 8% of variation. However, when pre-pubertal DLWG was evaluated on a continuum from 0.5 to 1.1 kg/d there was no effect (Van Amburgh *et al.*, 1998).

1.3.1.3 Post pubertal growth rate

Following release of oestradiol from the ovaries during the first oestrous cycle, ductal structures in the mammary gland begin to rapidly branch and lengthen (Capuco and Ellis, 2013). If these duct structures are unable to support the markedly increased rate of epithelial cell proliferation during the second allometric period, then this would have a detrimental effect on milk yield (Brown *et al.*, 2005). However, there is a lack of research regarding associations between growth and mammary development in the second allometric period. On most UK units, heifers need to fit into the main cow feeding system and

require low input to reduce total cost of heifer production (Garnsworthy *et al.*, 2019). The authors concluded it is not fully understood exactly what heifers are being fed; with most systems adopting practices to reduce feed costs such as incorporating poor quality silage or feed refused by the milking herd into heifer rations or grazing youngstock on poorer pastures towards farm boundaries. By doing so it is difficult for growing heifers to be fed to their requirements and effects of these practices on future performance require further research.

A few authors disagree with high feeding levels after puberty, reporting that DLWG in post-pubertal heifers becomes less important because rapid growth during this period does not positively affect mammary development (Sejrsen *et al.*, 1982a) or subsequent milk production in the cow (Hoffman *et al.*, 1996; Zanton and Heinrichs, 2007). Additionally, Lacasse *et al.* (1993) noted heifers fed a higher plane of nutrition in the isometric phase of mammary development after puberty had an increased milk fat content. Similarly, Hoffman *et al.* (1996) found that higher BCS was associated with heifers fed an accelerated post-pubertal diet. There was no effect of an accelerated diet on first lactation milk yield, but the authors pointed out that this may be due to lower DMI during the first lactation.

On the other hand, Meyer *et al.* (2004) reported that dietary mistakes made in the second year of heifer rearing period led to impaired lactation performance, i.e., reduced daily milk yield and compromised fertility. Storli *et al.* (2017) confirmed that the importance of post-pubertal period is consistent with increased growth and mammary parenchyma development that occurs from the onset of puberty, and that growth rate between 365 and 456 days (10 and 15 months) has a significant bearing on first lactation yield with optimum DLWG being 0.83 kg/d. The authors noted that optimum DLWG should be dynamic, increasing from genetic selection over time, and proportionally adjusted during the pre-pubertal period to account for a higher DLWG at lower ages. Similarly, Berry *et al.* (2009) and Macdonald *et al.* (2005) found that heifers produced more milk due to post-pubertal feeding rather than pre-pubertal. Berry *et al.* (2009) thought that larger frame size and expected higher DMI potential in higher-yielding heifers, compensated for any reduced mammary development

in larger heifers, masking the negative effect of pre-pubertal growth rate on milk production. Macdonald *et al.* (2005) suggested that post-pubertal feeding should be such that younger heifers achieve similar LW to those heifers calving at a later age if excessive body condition at calving is not to compromise DMI and subsequent health. In support of this, Lacasse *et al.* (1993) found no negative effect on mammary parenchymal tissue growth or subsequent milk production in pregnant heifers grown slowly to 365 days (12 months) and then fed for rapid growth during the second allometric phase of mammary development. As a result, Lacasse *et al.* (1993) concluded that higher planes of nutrition during gestation have a positive effect on mammogenesis. Lastly, Krpalkova *et al.* (2014) found that the post-pubertal period has the greatest influence on AFC, and high DLWG (>0.85 kg/d) between 152 and 426 days (5 and 14 months) of age was associated with an AFC 22 days lower (approximately one oestrous cycle of heifers).

Nutritional strategies for optimum mammary development

Some studies suggest a stair-step approach to prevent adverse effects on mammary development. For example, Ford and Park (2001) trialled a three-step programme in dairy heifers between 183 days (6 months) and first calving. The programme was designed to induce compensatory growth during the re-alimentation phase, which coincided with hormone-sensitive developmental stages (pre-puberty, puberty and mating, gestation). Overall, stair-step heifers gained more LW (0.95 versus 0.80 kg/d) and consumed less feed (8.8 versus 11.3 kg/d), resulting in a 1.5-fold increase in the growth efficiency (10.8 versus 7.2%) in comparison with conventionally fed control heifers. This was said to benefit mammary development and milk production in the first and second lactations, but only four animals per group were used. Similarly, Park *et al.* (1989) observed that the intensity of mammary development induced by a stair-step compensatory growth pattern was greater than that of heifers fed conventionally. However, Dawson and Carson (2004) tested a step feeding model on dairy heifers with restricted growth either pre-pubertally or in early pregnancy and found no benefit through subsequent compensatory growth. Although, feed costs may be reduced this way by making use of compensatory

growth mechanisms during the well-fed periods (Mourits *et al.*, 2000a), ensuring animals are offered high energy feed sources and supplements during re-compensation is most critical to meet the increased energy requirement.

One study found that the risk of greater mammary fat disposition from increased energy and protein uptake was only high between 56 and 98 days of age and could be fed without detriment between 14 and 56 days of age (Brown *et al.*, 2005). Another study also found that pre- and post-weaning diets which balance the ratio of metabolisable protein to energy, e.g. feeding 38 g of metabolisable protein per Mcal of metabolisable energy, can allow DLWG up to 1 kg/d without excessive adipose tissue deposition in the mammary gland or reduced first lactation yield (Albino *et al.*, 2015). Faster growth may also be indicative of metabolic efficiency, implying that metabolically efficient calves continue to be metabolically efficient as adults (Sejrsen *et al.*, 2000). Lastly, high pre-pubertal DLWG which corresponded with adequate skeletal growth was not associated with impaired mammary growth (Sejrsen *et al.*, 1982a) and reduced milk yield (Swanson, 1960; Little and Kay, 1979). Therefore, recommendations based on DLWG alone are misleading because growth may be due to desirable skeletal growth or undesirable fat deposition. Many researchers use only LW as the growth parameter, which makes it difficult to make useful comparisons among studies. Abeni *et al.* (2000) suggested that time to puberty, and so time available for allometric mammary growth, may have a greater effect on first lactation yield than accelerated LW gain during this time.

Accelerating pre-pubertal growth of Holstein-Friesian heifers by providing higher concentrations of protein in the ration does not decrease milk production (Lammers and Heinrichs, 2000). In fact, it has been suggested that protein is a limiting factor to achieving accelerated heifer growth (Van Amburgh *et al.*, 1991; VandeHaar, 1997). Capuco *et al.* (2014) indicated that limiting protein is particularly problematic during the early post-weaning period. By supplying a diet of high protein and energy from 122 days (4 months) of age until the luteal phase of the fifth oestrous cycle, Radcliff *et al.* (1997) increased growth rate to 1.2 kg/d (controls at 0.80 kg/d) without negatively impacting mammary

development, and reduced age at puberty without hindering LW or skeletal size at puberty.

Inclusion of protein sources vary (e.g., soybean meal, rapeseed meal and dried distiller's grains), and can be adjusted according to the ratios of silage (e.g., grass, whole crop, and maize). However, heifer diets should be formulated with minimal dietary crude protein (CP) concentration for optimal growth to prevent excessive nitrogen excretion. A heifer with 40% MW would require dietary CP of 117 g/kg DM to achieve a DLWG of 0.7 kg/d, 123 g/kg DM for a DLWG of 0.8 kg/d and 129 g/kg DM for a DLWG of 0.9 kg/d (NRC, 2001). However, NRC (2001) guidelines are generally accepted as an underestimate (Margerison and Downey, 2005), with heifer diets varying in CP concentrations between 119 g/kg DM (Zhang *et al.*, 2017), 130 g/kg DM (Hoffman *et al.*, 2001) and 160 g/kg DM (Hill *et al.*, 2008a). Dietary protein utilisation in heifers is different to lactating adult cows as protein is prioritised for growth rather than milk production. Reducing the impact of excess nitrogen excretion has led to development of models indicating that dietary CP concentration can be as low as 137 g/kg DM without significantly reducing growth rate, mammary development, and age at puberty (Whitlock *et al.*, 2002). However, additional dietary protein may prove effective in enabling high rates of body and skeletal gain without excessive fattening (Van Amburgh *et al.*, 1991). Management systems that increase skeletal growth rate might be used to accelerate body growth by utilising protein sources without increasing fattening, thus preventing detrimental effects of accelerated growth on mammary development and potential effects on lactation (Kertz *et al.*, 1987; Radcliff *et al.*, 1997; VandeHaar, 1997; Lammers and Heinrichs, 2000).

According to Preston (1966), the protein to energy ratio should be higher in faster growing heifers since protein requirement increases at a faster rate than energy. It was said that as the protein to energy ratio is more of a function of DLWG than LW, the ratio should remain similar as the heifer matures. However, NRC (2001) gives a lower protein to energy ratio to heifers over 183 days (6 months) than those below. Furthermore, recent research (Radcliff *et al.*, 1997; VandeHaar, 1997) suggests that insufficient concentration of dietary CP in

rapidly growing pre-pubertal heifers may impair mammary development and decrease subsequent milk production. Lammers and Heinrichs (2000) found that a higher ratio of dietary protein to energy ratio increased structural growth more than DLWG and lowered rate of increased BCS, which suggests an increase in lean tissue growth.

Additionally, heifers offered a diet high in rumen undegradable protein (RUP) to support a DLWG of 0.9 kg/d from 183 to 395 days (6 to 13 months) of age had the highest LW, DMI, and feed efficiency (Bethard *et al.*, 1997). Incorporation of additional dietary protein, supplied as RUP, can provide rapid growth and larger framed heifers, without associated decreases in pre-pubertal mammary development or milk production (Capuco *et al.*, 2004). However, whether RUP supplementation in heifer-rearing programs is more effective than supplementation with rumen-degradable protein remains to be rigorously studied.

1.3.2 Live weight at first calving

Heifers calving early with insufficient LW and frame might be a reason for reduced performance during first lactation, particularly if mammary gland efficiency was not maximised by post-pubertal nutrition and nutrients were not shifted towards growth during lactation (Ettema and Santos, 2004; Lohakare *et al.*, 2012). However, heifers calving late, and possibly with a greater BCS, may also not reach their milk yield potential in first lactation (Van Amburgh *et al.*, 1998).

Studies support the suggestion that greater first lactation milk yield can be achieved in younger calving heifers providing they calve with sufficient maturity (Ettema and Santos, 2004; Cooke and Wathes, 2014). Clark and Touchberry (1962) first set out to answer the question if it is more economical to delay calving to obtain greater milk yield in first lactation due to increased age and LW. It was concluded that additional costs in feed and labour outweighed higher first lactation milk yield, but also that LW was four times more influential on first lactation milk yield than AFC alone. Likewise, Dobos *et al.* (2001) reached the same conclusion that, although AFC independently affects milk yield, LW was

two to three times more influential and suggested the negative impact of earlier calving could be compensated by calving heifers with greater LW following economical evaluation. Likewise, Van Amburgh *et al.* (1998) found heifers calving at 21.3 months had a 5% reduction in 4% FCM compared to heifers calving at 24.5 months due to their lower LW and not to a direct effect of younger calving age.

This positive effect of greater calving LW on first lactation milk yield has been reported by various studies (Keown and Everett, 1986; Hoffman and Funk, 1992; van der Waaij *et al.*, 1997; Carson *et al.*, 2002; Macdonald *et al.*, 2005). Keown and Everett (1986) found heifers that weighed 567 kg at first calving produced 806 kg more milk in first lactation compared to heifers with a LWFC less than 408 kg. As a result, the authors recommended mating Holstein heifers according to LW not age, and to calve with LW between 544 and 567 kg to maximise first lactation milk yield. Heinrichs and Heinrichs (2011) concluded that calving ease (defined as difficulty of the heifer's birth) and LWFC had significant effects on first lactation milk yield in Holstein heifers. Calving ease was negatively associated with milk production and LWFC was positively associated. However, it has been found that heifers calving with greater LW are less economical than their lighter peers (Dawson and Carson, 2004). This was because greater rearing costs, associated with additional feed costs to achieve higher growth rate, outweighed the greater return from higher first lactation and lifetime yields in heifers calving with more LW.

Heifers calving with excessive LW or high BCS are not desirable as they are found to have a poorer appetite and experience greater LW losses during lactation (Davenport and Rakes, 1969), lower milk yields (Garnsworthy and Topps, 1982) and a higher risk of dystocia (Rice and JN, 1972) and metabolic conditions such as fat cow syndrome (Morrow, 1979). Similarly, Hoffman *et al.* (1996) indicated that heifers which are not pregnant by 487 days (16 months) of age may have undesirably high LW and BCS at first calving. These heifers will be extremely susceptible to ketosis, displacement of the abomasum, and low feed intake in the transition period.

Hoffman *et al.* (1996) could not determine the exact mechanisms which resulted in heifers calving early with a similar pre-calving LW to later-calving heifers, but with lower post-calving LW and first lactation performance. Higher LWFC is thought to increase a heifer's potential DMI during first lactation. This is important in terms of milk yield. Smaller and lighter heifers at first calving may struggle to compete for food with older cows in the herd, resulting in reduced DMI and greater LW and BCS losses (Grant and Albright, 2001). Additionally, if maturity at calving is not adequate in heifers with greater genetic potential for milk production, then these heifers are more likely to experience metabolic consequences during first lactation which might affect fertility (Ettema and Santos, 2004).

1.3.2.1 Targets for live weight at first calving

Defining a target LWFC is complex. Firstly, due to differences in mature LW between breeds and secondly, LWFC is a function of both management and genetics. The LW at which a heifer calves depends on both her age at conception and growth rate throughout the rearing period; both of which can be influenced by management decisions relating to AFS and feeding of heifers (Carson *et al.*, 2002). This suggests that once the most efficient or productive LW has been selected or determined genetically, the replacement heifer should be raised to maximum frame weight or beyond so that some adipose tissue deposition occurs for energy mobilization during the first lactation (Hoffman and Funk, 1992). Targets for LWFC in Holstein-Friesian heifers have been suggested between 515 to 600 kg to maximise first lactation performance (Remer, 1976; Moore *et al.*, 1991). However, a recent study has suggested a greater LWFC up to 620 kg (Krpálková *et al.*, 2014b) and that high concentrate intensive feeding systems may need higher targets between 540 to 650 kg (Keown and Everett, 1986; Heinrichs, 1993; Hoffman, 1997), whereas lower targets of 490 to 550 kg may be sufficient in pasture-based systems (Holmes *et al.*, 1987; McLean and Freeman, 1996).

Margerison and Downey (2005) suggested LW targets in terms of proportion of MW were a more accurate representation than absolute LW, and a target MW of 85 to 90% at first calving was desirable. However, proportion of heifers

achieving target LW differed between breeds at different ages (McNaughton and Lopdell, 2012; Handcock *et al.*, 2016), indicating that the appropriate target percentage may be different among breeds. The MW is generally estimated from average LW of mature cows in the herd (third parity cows and above), which is subject to many factors such as physiological and nutritional status, but the target maturity concept provides a valuable rule of thumb method for managing heifers. Boro *et al.* (2016) concluded that the target maturity concept is one of the best management tools for raising dairy heifers.

1.3.3 Dry matter intake

Interest in dairy cow behaviour and welfare is rising due to their associations with greater milk production. In simple terms, cows that are healthy eat more dry matter, and cows that eat more dry matter produce more milk. However, the most efficient cows will produce milk with DMI below the level predicted from their milk yield. Heifers in first lactation tend to produce less milk than older dairy cows (DePeters *et al.*, 1985; Buckley *et al.*, 2003). This is most likely because they have a lower DMI, with one study concluding that DMI of heifers in their first lactation was 22% less than that of multiparous cows (Azizi *et al.* (2009). In addition to diet composition and energy requirement, DMI is influenced by various factors, including physiological differences, management system, behaviour and social interactions within the herd (Grant and Albright, 2001; DeVries and von Keyserlingk, 2005; DeVries *et al.*, 2005). Therefore, it is important to review factors which drive DMI, and consequently milk yield.

1.3.3.1 Feed conversion efficiency

Improving feed efficiency has been listed as a top three measure to reduce greenhouse gas emissions (Knapp *et al.*, 2014). The efficiency that dairy cattle can convert feed into milk is vital as it has a major bearing on-farm profits. Feed costs are estimated to make up 70% of total variable cost of milk production (Smith, 1976) and therefore the herd must have high FCE. Measuring FCE is useful for evaluating performance of farm feeding and management systems when trying to identify opportunities for improvement (Beever and Doyle, 2007). Parity number affects FCE as heifers in their first lactation still require a portion

of their energy intake to support growth and therefore, in comparison to older dairy cows, may have a lower FCE (Van Arendonk *et al.*, 1991). Stage of lactation causes variation in FCE as early lactation cows are in negative energy balance, which increases FCE, compared with dairy cattle in later lactation that are gaining LW (Al-Marashdeh *et al.*, 2020). Dairy cattle with lower LW are suggested to have higher FCE as they have lower requirements for maintenance and more energy can be used to produce milk (Veerkamp, 1998). However, in a study by Al-Marashdeh *et al.* (2020), FCE was found to be greater in dairy cattle with higher LW, regardless of stage in lactation.

1.3.3.2 Production system

Recent studies have found that differences in systems and management practices can significantly impact individual cow intake, behaviour, and performance (Grant and Albright, 2001; DeVries *et al.*, 2005). Animal characteristics influencing DMI in housed and grazing systems are likely to differ. For example, rumen capacity is likely to have a greater influence on DMI in grazing production systems because of the high gut-filling capacity associated with grass (Freer, 1981). Furthermore, cattle genotypes that can digest and absorb digesta from high-starch diets without any undesirable digestive consequences are likely to perform best in housed systems, whereas the ability to digest forage, and the urge to graze, are likely to be characteristics of high DMI in grazing production systems (Berry *et al.*, 2014).

Cows should be allowed to perform natural behaviours to ensure high welfare standards and milk yield (Grant and Albright, 2001). Feeding is a predominant behaviour trait in ruminants, as it takes priority over any other. Typically lactating dairy cows spend 3 to 5 hrs/d eating, 7 to 10 hrs/d ruminating and up to 14 hrs/d lying (Grant and Albright, 2001; Proudfoot *et al.*, 2009). Conventional milking systems (CMS) where cows may be driven to the milking parlour up to three times daily, daily behaviours such as ruminating, feeding, and lying, are organised around the timing and duration of parlour milking (Gomez and Cook, 2010). When this restriction is removed, studies have shown that feeding and milking are more distributed over 24 hrs (Olofsson *et al.*, 2000) and cows may partition more time at the feed bunk at night than during the day (Helmreich *et*

al., 2014). Cow behaviours are often assessed by visual observation or video recording. However, automation and precision technologies, such as rumination collars and automated milking and feeding systems, which have become a popular approach to improve overall productivity and efficiency (Bewley *et al.*, 2010), can also be used to measure individual cow behaviour.

In an automatic milking system (AMS), cows have greater freedom over their time budget. For example, cows spend less time in the feeding area during the day, and more time at night (Helmreich *et al.*, 2014). Rumination activity, if linked to lying times, can also be variable. Cattle typically spend 9 to 12 hrs/d lying (Webster, 1993), but in an AMS periods of lying may be shorter and more frequent (Helmreich *et al.*, 2014). Increased lying time may be because cows in an AMS spend less time standing while waiting to be milked. Subsequently, reducing standing decreases lameness, which may lead to higher milk production (Blowey, 2005). Nevertheless, an advantage of a CMS is cows tend to synchronise their behaviour through social facilitation (King *et al.*, 2016b), a strategy which may have been adapted to avoid predation (Cooper *et al.*, 2008) and can be beneficial for learning (King *et al.*, 2016b).

Herd competition

Dairy cows are very social, usually forming a herd hierarchy (Galindo and Broom, 2000; Solano *et al.*, 2016). Compared with adult dairy cows, heifers first entering the herd require more time to establish themselves within the social order of the herd, which may affect their feeding behaviour and DMI (Albright, 1993). Competition in the herd may result in socially subordinate cows being displaced more easily from the feed face (Huzzey *et al.*, 2006). Foris *et al.* (2019) reported that competition can lead to agnostic behaviour amongst the herd, which can decrease feeding time and DMI. Subordinate cows are most likely to be heifers in first lactation and/or cows of smaller size or less maturity (Neave *et al.*, 2017). Therefore, ensuring heifers calve with sufficient maturity and LW may reduce competition from dominant cows. Grant and Albright (2001) suggest that first lactation heifers with low LW will tend to eat less DM, potentially causing problems such as decreased milk yield and longevity. Conversely, although not directly measured, a greater degree of fatness at

calving could suppress DMI (Hayirli *et al.*, 2002), increase postpartum LW loss, mobilization of fat and circulating fatty acids, and thereby increase milk fat (Palmquist *et al.*, 1993).

The genetic correlation between feed intake in lactating cows and growing heifers is 0.67, however, selecting for increased body size and milk yield will, on average, increase genetic merit for DMI (Veerkamp and Brotherstone, 1997). On the other hand, cow size is negatively correlated with longevity and housing adaptability (Hansen, 2000), and thus selection for small cows should improve whole-farm profitability more than predictions based only on feed calculations. Additionally, bigger cows require more space. In terms of income-over-feed-costs on a whole-farm basis, if a system can handle more cows, then smaller cows have been found to be more advantageous (VandeHaar *et al.*, 2016).

Feeding space, design, and availability

Cows eat more when access to feed is ad-libitum and individual cow space at the feed bunk is increased (DeVries, 2019). It is expected that heifers in their first lactation consume less DM around fresh feed delivery due to bin displacement from older and more dominant cows (Neave *et al.*, 2017). Although competition for feed is inevitable, dominance has a greater effect at higher stocking densities and when feeding space and availability is limited (Longenbach *et al.*, 1999; Grant, 2004). Competition at the feed bunk increased standing time as cows waited by the feed bunk to gain access to feed (Olofsson *et al.*, 2000; Huzzey *et al.*, 2006), and excessive standing time was linked to lameness (Vermunt and Greenough, 1991; Singh *et al.*, 1993). Limiting access to feed bins or a feed bunk increased displacements from feed bins in several studies (Olofsson *et al.*, 2000; Huzzey *et al.*, 2006). Moreover, cows are known to have greater DMI when fresh feed is delivered frequently and routinely (DeVries *et al.*, 2005; Greter *et al.*, 2010). The results confirmed that a competitive feeding environment increased displacements at feed bins regardless of lactation number.

1.3.3.3 Feed behaviour

Feeding behaviours, such as daily feeding duration and feeding rate, have been associated with DMI and feed efficiency (Connor *et al.*, 2013; Halachmi *et al.*, 2016; Xi *et al.*, 2016). Daily feeding duration has been positively associated with milk yield (Gomez and Cook, 2010; Johnston and DeVries, 2018), although Azizi *et al.* (2009) found that there was no significant effect of milk yield on feeding behaviour.

For Holstein-Friesian cows in an AYR, housed system daily feeding duration has been found to range from 208 mins (Ben Meir *et al.*, 2018) to 312 mins (Krpálková *et al.*, 2021), whilst feeding rate ranges between 0.07 kg DM/min (Azizi *et al.*, 2009) and 0.26 kg/min (Krpálková *et al.*, 2021). Older cows tend to eat quicker to allow more time in the feed bin to process the higher amount of nutrients needed for their higher milk yield whereas heifers in their first lactation tend to eat slower and take smaller bites (Grant and Albright, 1995; Norring *et al.*, 2012). Krpalkova *et al.* (2021) found cows eating less than 0.14 kg DM/min had significantly greater DMI, milk yield, LW, feed conversion ratio and resting duration. Shorter feeding durations and faster feeding rates have also been associated with competition for feed (Llonch *et al.*, 2018) and can indicate rumen health. Longer feeding duration facilitates chewing and reduces particle size (Llonch *et al.*, 2018) and lower feeding rate facilitates saliva production, slower rumen passage and greater digestibility (Krpálková *et al.*, 2021). Therefore, reviewing management practices and feed factors which affect feeding time and feeding rate of heifers in their first lactation would be useful for attaining these benefits.

Meal timing and behaviour

Dairy cows consume 89% of their meals during the light phase of the day (0400 to 2200 hrs) (Dürst *et al.*, 1993) and consume the largest proportion of their overall daily intake (30%) between 1200 and 1800 hrs (Rottman *et al.*, 2014). This could be because naturally cows tend to ruminate and rest during the night hours and graze in the afternoon when nutrients are more available in pasture (Parsons *et al.*, 1983; Soriano *et al.*, 2000; Trevaskis *et al.*, 2001). In a CMS,

intake was associated with external events; five distinct peaks after milking (three times daily; 0500, 1300 and 2100 hrs), feed delivery (0900 hrs), and between the second and third milking (Ben Meir *et al.*, 2018). Heifers in their first lactation may deviate from this routine as they may be dominated at the feed bins driving them to consume meals at night (Foris *et al.*, 2019).

Meal duration in high-yielding cows ranges from 35 to 38 mins (Azizi *et al.*, 2009; Ben Meir *et al.*, 2018) and meal frequency ranges from 5.8 meals/d (Tolkamp *et al.*, 2000) to 8.7 meals/d (Azizi *et al.*, 2009). Short and more frequent meals are associated with higher feed digestibility, which is a key factor in improving feed efficiency (Robinson and Oddy, 2004; Llonch *et al.*, 2018), as well as better rumen health (King *et al.*, 2016b). However, Robinson and Oddy (2004) and Llonch et al. (2018) used beef cattle and different meal criteria. Robinson and Oddy (2004) defined a meal as a feeding session where a second session by the same animal within 2 min of the end of the previous feeding session was considered as part of the previous session, and Llonch *et al.* (2018) defined a meal as a feeding event that was refined by eliminating visits in which no feed was consumed and those shorter than 1 min in duration. Furthermore, feeding competition has been shown to cause heifers to consume fewer meals per day, which are larger and longer in duration (DeVries and Von Keyserlingk, 2009). This agrees with Azizi *et al.* (2009) who found adult cows have bigger meals because they tend to eat quicker. Further research into meal behaviour, feed efficiency and performance of high yielding dairy cows is recommended.

1.3.3.4 Feed factors

Transition dairy cows are vulnerable to the negative consequences of depressed feed intake around calving (Proudfoot *et al.*, 2009). Because recent research has identified minor decreases in DMI before calving as a risk factor for disease post-calving (Huzzey *et al.*, 2006), further work is needed to assess the effects of feed factors on disease incidence and performance after calving.

Newly-calved cows should be fed for optimal health and expensive supplements are warranted, whereas cows in peak lactation should be fed

minimum fibre diets with plenty of digestible starch to maximize energy intake (VandeHaar *et al.*, 2016). Cows in later lactation should be fed to optimize milk and body condition. Ideally, they should be fed less fermentable starch and more fermentable fibre to promote partitioning of nutrients toward milk instead of body tissues and thus minimize fattening, and lower protein to maximize efficiency of protein utilisation (Allen and Piantoni, 2014; Boerman *et al.*, 2015).

Neutral detergent fibre (NDF) concentration of the diet can influence heifer DMI. Hoffman and Kester (2013) found heifers consume 1% of their LW in NDF regardless of body size, therefore diets with low NDF (e.g., maize silage) will increase DMI and high NDF (e.g., straw) will decrease DMI. Heifers selectively sort against large particles (Greter *et al.*, 2010), showing preference for particles less than 8 mm; but, selection was not affected by feed bunk stocking rate (Coblentz *et al.*, 2018). Shorter particle size has been found to increase DMI (Kononoff *et al.*, 2003; Kammes and Allen, 2012). Pelleting feed has been found to increase DMI, however, due to reduced fibre particle size pelleting potentially increases rumen emptying rate and reduces fibre digestibility (Bonfante *et al.*, 2016). On the contrary, reduced particle size might increase surface area available for bacterial attachment (Miron *et al.*, 2001), thereby increasing fibre digestibility. Reducing dietary particle size could be considered as a way of decreasing rumen fill, if rumen fill is restricting DMI (Montgomery and Baumgardt, 1965). However, as short particles of a ration are mainly the concentrate component, increased intake of short particles can reduce rumen pH and increase risk of digestive problems (DeVries *et al.*, 2008).

Rumen pH may be a greater concern when top dressing rations with concentrates as DeVries and von Keyserlingk (2009a) found heifers rapidly consumed concentrates in few, large meals before consuming the hay portion of their ration. Given this consumption pattern, some heifers may dominate the feed bunk in a group-feeding situation, particularly during peak feeding times, and consume more concentrates than intended. The authors concluded that feed delivery method is important when considering feeding, sorting, and competitive behaviours of growing dairy heifers. Heifers fed a top-dressed ration experienced greater feed competition, fed for longer immediately

following feed delivery, consumed shorter concentrate particles to a greater extent, and had lower NDF intake. Whereas a total mixed ration promoted a more even diurnal feeding pattern, minimized sorting and competitive behaviours, and resulted in more solid faecal consistency. Further research is needed to determine when these behaviours develop and how long they may persist in the life of the animal.

1.3.3.5 First lactation grouping

Some studies have shown that housing heifers in their first lactation separately can improve their DMI by 12%, feeding time by 11%, lying time by 9% and milk yield by 5% (Krohn and Konggaard, 1979). Additionally, a uniform group of cows allows for more accurate ration formulation. Feeding a single TMR across all cows can never maximize milk production and efficiency and is usually formulated for the higher producing cows. Therefore, the TMR is often less than optimal for heifers in their first lactation. For example, heifers calving before 700 days (23 months) had a similar milk yield in early lactation to heifers calving after 700 days (23 months) (Ettema and Santos, 2004). However, this was not seen after 50 DIM suggesting that the lactating ration may have been of insufficient nutrient density for early-calving heifers to grow and lactate. Additionally, heifers continue to grow throughout the first lactation which should be considered in ration formulation (Coffey *et al.*, 2006). This growth occurs at the expense of body condition and fertility and at a greater extent if inadequate energy is supplied. Moreover, feeding heifers in their first lactation a separate, and more accurate, ration can decrease excessive nutrient excretion and reduce environmental impact (St-Pierre and Thraen, 1999).

Nutritional grouping and multiple TMR undoubtedly increase capital, management, and labour costs; however, feeding cows according to requirement enhances production, efficiency, profitability, and sustainability of the industry (VandeHaar and St-Pierre, 2006). Moreover, it is important to feed to requirement to prevent unnecessary increases in feed costs and decreases in feed efficiency as excess energy intake by less efficient cows did not result in greater milk yield or LW, but was wasted as heat production and energy loss (Ben Meir *et al.*, 2018). The most efficient cows will use less feed for

maintenance, which increases energy allocated for milk production, thus increasing milk production per feed unit, and will dilute the methane cost associated with maintenance energy requirements. One approach might be to feed cows' supplements individually using a computerized feeding system that recognizes cows and dispenses specific mixes at timed intervals throughout the day (VandeHaar *et al.*, 2016). Depending on farm size and management practices this could be an option for some dairy systems.

1.4 Factors affecting survivability

Cows leaving the dairy herd early is a major loss to the dairy industry. The economic impact, however, is mainly defined by exit reason; a cow can be sold live, culled in an emergency or with no productive or economic value (involuntary or voluntary cull), or dies (Orpin and Esslemont, 2010c). In herds of constant size, a cow may be culled voluntarily if the upcoming replacement cow is deemed to have greater lifetime profit (Dijkhuizen *et al.*, 1985), but often there is insufficient scope for voluntary culls due to lack of replacements and high rearing costs. Cows culled voluntarily can be regarded as economic culls and may be removed from the herd due to low yield, aggressive behaviour, or sold to another herd for milk production (Orpin and Esslemont, 2010b). Involuntary culls include all other reasons, mainly illness, injury, and infertility, which make up 68% of culled cows (Bell *et al.*, 2010) and often incur a financial cost to the producer.

Rate of cows leaving the herd is poorly recorded in the UK. A recent NMR report found median culling rate in the UK was 28% (Hanks and Kossaibati, 2021). This is 3 to 4% higher than between 2010 and 2015, indicating overall cow longevity has decreased. From an audit of 843 British herds, the top three culling reasons were fertility, lameness, and udder health (Orpin and Esslemont, 2010c). Other studies have also reported these major culling reasons (Bascom and Young, 1998; Le Cozler *et al.*, 2010). In a survey of 302 UK herds, 25% of cows culled were barren, 17% had mastitis and 8% were lame (Kite Consulting, 2008), but could be as high as 27% with udder problems and 27% infertile (Chiumia *et al.*, 2013). However, in a study examining

pregnancy in 2502 cows sent to a British abattoir, 23.5% were found to be in calf, of which half were believed by the farmer not to be pregnant (Singleton and Dobson, 1995). Of all cows in the analysis by Orpin and Esslemont (2010), 23% were culled for 'sickness/ death and casualty', which equates to an annual culling rate of 5% of the national herd. Orpin and Esslemont (2010) found their average culling rate ranged from 10 to 32% between lower and higher quartile herds, with some herds culling no cows due to old age, poor yield, udder health, recumbency, casualty or other problems. It was therefore suggested that these culling reasons are not inevitable and can have a disproportionate economic and welfare impact on farms where these reasons are significant.

1.4.1 Cow fertility

Infertility remains a major cause of early removal of dairy cows. It is estimated that about 20% of cows fail to conceive annually due to poor fertility and/or management, and are culled (Orpin and Esslemont, 2010c). Culling for poor fertility is expensive and Esslemont and Kossaibati (2000) suggested a national target of wastage due to failing to conceive of no more than 7% of the herd. Economic loss from infertility includes decreased milk production, lower calf output and increased costs of keeping the cow dry for longer. Other costs may include impact of the slip in the calving pattern and additional AI and veterinary costs (Esslemont *et al.*, 2001). A low level of culling due to poor fertility increases profitability as dairy producers can sell high-yielding cows at a better price to continue milk production in another herd (Glover, 1997).

Bell *et al.* (2010) found fertility factors such as abortion (p<0.001), conception failure (p<0.001) and greater days between calving and conception (p<0.001), were associated with greater culling risk. On average, the interval from calving to first service in the UK is 83 days and the proportion of cows served by 80 DIM is 61% (Hanks and Kossaibati, 2021). This is 15% higher than in 2010, however, the proportion of cows that conceived by 100 DIM remains low at 37%. Esslemont (1992, 1993) found decreasing the period between calving and first service from 65 days to 50 days, reduced days to conception by 20 days and failing to conceive culling rate from 14% to 10%, and increased profitability (an estimated figure of £6232 per 100 cows).

One of the most common measures of fertility is calving interval. In the UK, median calving interval in 2021 was 397 days, 27 days less than in 2010 (Hanks and Kossaibati, 2021). This reduction was, in part, influenced by higher culling rates. However, an earlier AFC also tends to reduce calving interval (Clark and Touchberry, 1962). For example, heifers calving between 760 and 791 days (25 and 26 months) had lower subsequent calving intervals than heifers calving later than 791 days (26 months) (Evans *et al.*, 2006). Eastham (2012) studied follow-up fertility data on UK dairy herds and found heifers calving between 700 and 760 days (23 and 25 months) had the lowest calving intervals after each lactation in comparison with heifers calving after 1095 days (36 months) and concluded that the role of fertility was pivotal in maximising lifetime yields.

The appropriateness of a 365 day calving interval target has been debated in previous studies, with some researchers arguing that due to greater milk yields on UK farms, it is unrealistic to expect cows to calve every 365 days (Knight, 2005; Sorensen *et al.*, 2008). Knight (2004) proposed that a 15 to 18 months calving interval would reduce veterinary costs and minimise problems such as drying-off cows that continue to yield above 20 L/d. However, there is little evidence to support this theory, and studies have reported conflicting results when comparing 12 months versus 15 months intervals (Bertilsson *et al.*, 1997; Knight, 2005). Additionally, the financial impact of a longer calving interval needs to be considered as annual milk yield and number of replacements born is reduced, and a longer calving interval complicates seasonal patterns in block systems (Arbel *et al.*, 2001). Some producers may voluntarily extend the calving interval to control annual culling rates. However, retaining cows which should be voluntarily culled for poor economic value from one year to the next can increase risk of disease (Orpin and Esslemont, 2010a). This strategy may be more likely seen in AYR calving herds, therefore, longer calving intervals may be the result of minimising culls rather than a direct effect of fertility.

Metabolic imbalance has been associated with cows culled for infertility. Excessive LW loss after calving impacts energy balance and delays resumption of cyclicity (Butler and Smith, 1989). This is because cows with negative energy balance produce less IGF-1 which reduces follicular development in the ovaries

and fewer follicles are ovulated. Animals calving with excess body condition also has deleterious consequences. Carson *et al.* (2002) found heifers with BCS of 3.5 at calving produced slightly more milk in first lactation but had worse fertility than heifers calving with a BCS of 2.8. Older heifers calving after 30 months of age had the highest BCS of 3.8 at calving and tended to have worse fertility parameters in comparison to younger heifers calving with BCS between 3.1 and 3.4. Similarly, a Scottish study found that adult Holstein–Friesian dairy cows with above average BCS at last service, were five times more likely to be culled due to infertility (Chiumia *et al.*, 2013). Likewise, cows with BCS greater than 3.5 in early lactation were more susceptible to metabolic disorders (Roche *et al.*, 2009). For example, cows with higher BCS had more cases of ketosis, and previous cases of ketosis before serving reduced the likelihood to conceive at that service (Gillund *et al.*, 2001). The authors therefore suggested that monitoring body condition is important for timely detection of cows likely to have abnormal body condition at the time of service. Additionally, cows with low protein yield at 60 DIM were ten times less likely to be culled (Chiumia *et al.*, 2013). However according to Chiumia *et al.* (2013), in first lactation heifers, only BCS at last service increased the risk of involuntary culling due to infertility (odds ratio = 13·0). This was because first lactation heifers mobilised more protein reserves for growth, so had a greater milk protein yield at 60 DIM than cows in at least second lactation. The authors suggested that monitoring traits which indicate metabolic imbalance could assist in identifying cows at high risk of being culled and contribute to reducing the associated risk through a more effective timely decision.

1.4.2 Production and health

Improving a cow's productive lifetime reduces culling rate and increases net farm profit (De Vries, 2017; De Vries and Marcondes, 2020). However, average productive life in the UK has remained at a similar level in the last six years, as although heifers are calving earlier at 2.2 years (791 days) of age, they are also culled younger at 5.9 years (Hanks and Kossaibati, 2021). This gives a productive life of 3.7 years, which is unchanged since 2016, and fewer completed lactations than over five years ago.

Orpin and Esslemont (2010) found that DNA testing for potential longevity increased profit by £28 per cow for every additional month of life. Reducing a culling rate of 33% to 25% increased average number of lactations by 0.56, equating an additional 6.7 months of life. Using 2007 prices this increased profit per cow by £156 (Orpin and Esslemont, 2010c). Stott (1994) suggested greater productive life is more valuable in lower yielding herds (~7500 L/cow/year) as longevity added £35 for every lactation to economic potential of replacement heifers valued at £1,500. Orpin and Esslemont (2010) calculated that the greatest economic loss is incurred in cows that leave the herd within 50 DIM due to death (£3,499) and the lowest is incurred in cows that are sold live after the end of a lactation (£1,238). Moreover, Bell *et al.* (2010) found that 58% of involuntary culls occur in cows before their fourth lactation, further reducing the likelihood of achieving maximum profit and productive potential. Because of this, a healthy, well-managed herd can have the same culling rate as a herd with poor management but is more profitable because a greater proportion of cows with greater productive life can be removed at the end of their lactation instead of through involuntary culling or death.

Bell *et al.* (2010) found cows with mastitis ($p<0.05$) were at greater culling risk, as were older cows ($p<0.01$) and cows with few DIM ($p<0.001$) were more likely to be culled. In a study of 35 US herds, older cows were most likely to die from udder or miscellaneous problems (Milian-Suazo *et al.*, 1988). The authors compared lactations with and without disease and found that cows with clinical mastitis were 2.0 times more likely to be culled and cows with teat problems and 2.7 times more likely to be culled. Cows diagnosed with disease were most likely to be culled either the same day or within 30 days of diagnosis, with cows diagnosed with milk fever, downer syndrome, displaced abomasum or problems with the teat, leg or foot emergency culled thus incurring a greater expense (Milian-Suazo *et al.*, 1988). Additionally, Chiumia *et al.* (2013) found cows that had a rapid increase in milk yield after calving were five times more likely to be culled due to an increased risk of udder problems. Cows with high milk yield acceleration were likely to have been under physiological pressure to satisfy increased nutrient demand for milk production. This stress increased

susceptibility of cows to disease and problems related to udder conformation (Chiumia *et al.*, 2013).

From limited UK data, annual disease rates for dairy cows are estimated to be as much as 50% for mastitis and about 60% for lameness (Orpin and Esslemont, 2010c). A recent NMR report found annual mastitis incidence from 252 herds was 27%, a reduction of 9% since 2016 (Hanks and Kossaibati, 2021). The report also found the proportion of cows completing lactations with no high SCC recordings in 2021 was almost half (48%), which is an improvement from a third of cows (33%) in 2010.

1.5 Research objectives

The foregoing discussion provides evidence that rearing replacement heifers is no longer seen as a separate activity but an integrated aspect of the dairy enterprise. This includes utilisation of feed and associated rearing costs. However, it is difficult to estimate rearing costs accurately due to variations in systems and lack of heifer data. There is an increased uptake of automation and a shift towards AYR systems to support higher yielding cows. Therefore, a better understanding of rearing costs and how cows interact in AYR systems is required. Literature agrees that AFC is a key indicator of both success of the rearing program and of productive herd life. Moreover, a growing body of research supports how AFC and replacement rate are key to improving efficiency of a herd and reducing its environmental impact. However, many producers do not achieve the optimum target of 730 days (24 months), and explanations for this need to be understood. This means that a large majority of the UK dairy industry is potentially overlooking gains in sustainability and profitability from improving efficiency in the rearing period.

Additionally, there is great variation within heifers managed on the same herd as well as various biological interrelationships associated with heifer growth. It is necessary to balance both positive and negative impacts on costs, milk production, and animal welfare, however, research on relationships between these factors is lacking. Ideally the key objective of rearing dairy replacements for every system is to correctly grow heifers so that they can calve with minimal

difficulties at an age and LW at which their milk production and profitability are maximized.

1.5.1 Working hypothesis

The main objective of this series of studies was to assess factors related to rearing heifer replacements that are associated with WFFE. Chapter Three will provide a retrospective overview of rearing efficiency in the study herd by quantifying variation between heifers in achieving rearing targets. This is with the reasoning that dairy systems must look beyond milk yield to expose inefficiencies in herd performance.

From the literature we understand that GED and BRD are the leading causes of heifer morbidity. With this in mind, the thesis first addresses the hypothesis that heifers treated more frequently for disease will grow slower and calve at an older age. Neither heifer LW nor GED treatment were recorded in the study herd until 2020. Therefore, Chapter Four set out to analyse GED in a prospective study, and Chapter Five provides a retrospective analysis of BRD. Based on the premise that, in the UK, GED incidence is poorly recorded and there is increased uptake of automated feeding, Chapter Four examines the effect of GED on feeding behaviour and heifer growth rate to weaning. In the second of the two health studies, Chapter Five examines effects of BRD on AFC and rearing costs, and using the culled cohort in the dataset, also assesses effects of BRD on lifetime performance, which is largely unknown due to lack of lifetime studies. Disease is also associated with poor fertility, therefore, the hypothesis is tested in Chapter Six that variation in AFC is a result of poor heifer fertility, or a management decision to defer mating of some heifers. Chapter Six assesses heifer fertility in a retrospective analysis by evaluating effects of days between first service and successful service (diagnosed pregnant), on AFC and lifetime performance.

The subsequent chapters are based on findings that heifers must survive beyond 1.5 lactations to repay their rearing costs (Boulton *et al.*, 2017). Therefore, Chapters Seven and Eight test the hypothesis that heifers calving at target age and LW at first calving, have greater productivity and survivability in

the milking herd. In a prospective study, Chapter Seven addresses how to minimise challenges during first lactation in two parts. Firstly, to compare effects of parity on behaviour and first lactation performance; and secondly, a subgroup analysis of first parity cows to compare effects of LWFC on behaviours and first lactation performance. Lastly, Chapter Eight seeks evidence to support the hypothesis that heifers calving at 730 days (24 months) spend a greater proportion of their lifetime lactating, which improves farm efficiency.

In summary, the main aims of this work focus on age and LW at first calving and how these; 1) are affected by calf health, 2) influence first lactation performance, 3) affect longevity and lifetime performance, and 4) suggest heifer rearing strategies which optimise all of the above.

Chapter 2

General material and methods

2.1 History and development

The Nottingham University Dairy Centre (NUDC) was established in 2003 on a greenfield site next to the Sutton Bonington Campus (Sutton Bonington, Leicestershire, UK, 52°50’21.4” N 1°15’02.1” W). The centre replaced outdated buildings in the nearby village of Kingston-on-Soar that housed a commercial dairy herd, and an old cowshed that housed a 36-cow research herd. The centre was initially designed for 180 cows and their replacements in an all-year-round (AYR) calving and housing system with robotic milking. Housing consisted of an open-span freestall barn with three milking-cow pens fitted with an automatic milking system (AMS; Fullwood Merlin, Fullwood Ltd., UK) and three calving pens, a group-housed calf shed, a heifer rearing shed, and a bulling-heifer shed.

In 2008, the herd was expanded to 240 cows with an addition of a fourth pen for milking cows and an extension of the heifer rearing shed. AMS were replaced by Lely Astronaut A3 (Lely Ltd., UK).

In 2012, individual calf hutches were introduced to combat spread of disease from older calves to new-born calves, which was an issue with group-housed calf pens, and to increase calf-rearing capacity.

In 2016, a grant was awarded by Innovate UK, with match-funding from the University of Nottingham, to establish the Centre for Dairy Science Innovation (CDSI), which is part of the national Centre for Innovation Excellence in Livestock (CIEL). The grant was used to build new sheds for research on nutrition (Nutrition barn), space allowance (Flexible housing barn) and mastitis (Category 2 containment unit); and a second group-housed calf shed and a second heifer rearing shed. The target herd size for CDSI was 360 cows, so no heifers were sold from 2016 onwards and all cows were mated with sexed semen. Cows were moved into the new barns in December 2017 and CDSI was officially opened in May 2018. Target herd size was reached in 2021.

Additionally in 2018, following a Home Office Inspector’s condition for designation and Tesco’s policy change on individual calf housing, calf hutches

were replaced with pair-housed pens. In 2020, a new calf-rearing unit was built with capacity to house 72 calves in pair-pens with automatic feeding and weighing from birth to weaning.

2.2 Youngstock management

2.2.1 New-born calf protocol

Directly following birth, all calves were collected from a straw-bedded calving pen and transferred to calf housing where they received 3-4 L of unpasteurised colostrum via oesophageal tube. All colostrum was quality checked using a colostrometer (a hydrometer that estimates immunoglobulin (Ig) G density by measuring colostrum density) and accepted at Brix value ≥ 22% (equivalent to ≥ 50 g/L of IgG). This was followed by 3 L of transition milk (pooled from first to third milkings of post-calving cows before whole milk is produced) fed twice daily via slow-flow teat buckets for the three subsequent meals.

2.2.2 Pre-weaning housing and nutrition between 2007 and 2020

From birth to 21 days of age, calves born between 2007 and 2012 were housed in straw-bedded pens in small groups (between 4 and 6), calves born between 2012 and 2018 were housed in individual hutches outdoors, and calves born between 2018 to 2020 were pair-housed in straw-bedded pens. After three meals of transition milk, calves were offered a whey-based milk replacer (MR; mean 6 L/d; concentration 150 g/L of Advanced SuperStart, Advance Sourcing, UK) via slow-flow teat buckets until calves were moved to a group calf pen at approximately 21 days of age.

At approximately 21 days of age, all calves were moved to a group calf shed and mixed with calves of similar age. The group calf sheds each had two straw-bedded pens (12m x 6m) fitted with a ventilation tube and one feeding station per pen operated by an automatic calf feeder (ACF; COMPACT smart, Förster-Technik, Germany).

On arrival at the group pen, calves were identified with a radio-frequency identification tag and registered to the ACF. MR was then offered to calves via the ACF, programmed with a 64 days feed curve for stepdown weaning by 85 days of age. A cereal-based starter concentrate (FiMLAC Sweet Start Pellets, Massey Feeds, UK), chopped cereal straw and fresh clean water were provided *ad-libitum* from 7 days of age to 14 days post-weaning (Table 2.1).

Table 2.1: Typical chemical composition of heifer calf diet offered before 2020

Composition (% DM, except where shown)	Milk replacer[1]	Starter concentrate[2]	Straw
ME, MJ/kg DM	21.5	-	-
Dry matter	95.6	87.3	91.1
Crude protein	23.0	17.5	6.3
Crude oil	20.0	5.0	1.9
Crude fibre	0.03	10.5	-
Neutral-detergent fibre	-	-	75
Crude ash	7.5	7.3	10.2

[1] Milk replacer ingredients: whey powder protein, whey powder, refined vegetable oil (palm, coconut), delactosed whey powder, hydrolysed wheat protein, whey permeate powder, glucose syrup, calcium carbonate, magnesium acetate ws, yeast product (safmannan), calcium butyrate

[2] Concentrate ingredients: barley, soya hulls, wheatfeed, wheat palm kernel exp, hi-pro soya, beet pulp, maize distillers, ext rapeseed meal, confectionary products, molasses, sopralin, maize, maize gluten, calcium carbonate, sodium chloride, vegetable fat, FiMLAC calf premix (inc. agrimos 2.5 kg/t), soya oil, carneo boost 10

2.2.3 Post-weaning housing and nutrition

After weaning, at approximately 90 days (3 months) old, all heifers were moved in their age groups to the rearing sheds. These sheds consisted of two buildings, each containing five straw-bedded pens and an automatic slurry scraping system (CleanSweep, Dairymaster, Ireland). Heifers moved in their age groups about every 21 days along the pens in the rearing sheds, until approximately 365 days (12 months) of age where they were then housed in the bulling-heifer shed. This shed contained two pens, each housing approximately 40 heifers and fitted with free-stall cubicles, sawdust-covered rubber mattresses and an automatic slurry scraping system (CleanSweep, Dairymaster, Ireland). Heifers were housed in the bulling-heifer shed until approximately 456 days (15 months) of age, or diagnosed pregnant (PD+), and were then moved to a pen in the main dairy barn fitted with free-stall cubicles, sawdust-covered rubber mattresses and an automatic slurry scraping system

(CleanSweep, Dairymaster, Ireland). At 21 days pre-calving, heifers were moved to a straw-bedded calving pen and mixed with adult dry cows in groups of 7 to 10 until calving.

From weaning until 21 days pre-calving, heifers were offered a mixed ration which was top-dressed with a pelleted concentrate (Rearing Nuts, Massey Feeds, UK) when heifers first entered the rearing shed (Table 2.2). At 21 days pre-calving heifers and dry cows were offered a transition diet which consisted of a specialised TMR containing transition minerals (Table 2.2).

Table 2.2: Typical ingredients and chemical composition of rearing diet fed to heifers and transition diet fed to animals three weeks prepartum

	Heifer concentrate [1]	Mixed ration	
		Heifer	Transition
Ingredients (g/kg dry matter):			
Grass silage	-	229	99
Maize silage	-	275	165
Whole crop silage	-	209	237
Wheat straw	-	9	247
Soyabean meal	-	84	72
Rapeseed meal	-	91	75
Molasses	-	27	-
Minerals	-	22	106
Fat supplement	-	19	-
Sugarbeet pulp	-	20	-
Soya hulls	-	7	-
Dried distiller's grains with solubles	-	7	-
Total	-	1000	1000
Composition (% DM, except where shown):			
ME, MJ/kg DM	-	11.8	9.8
Dry matter	87.3	45.2	65.6
Crude protein	16.0	16.8	-
Crude oil	4.6	4.5	-
Crude fibre	8.1	-	-
Neutral-detergent fibre	-	35.5	-
Crude ash	7.4	7.5	-
Starch	-	15.3	-

[1] Concentrate ingredients: barley, wheatfeed, ext rapeseed meal, palm kernel exp soya hulls, maize germ, molasses, calcium carbonate, sodium chloride, vegetable fat

2.2.4 Youngstock health

All calves were vaccinated against respiratory disease (Rispoval RS+Pi3 IntraNasal, Zoetis) at 9 days of age and all sick calves were isolated upon diagnosis of disease. Calf jackets were routinely used in temperatures below

15 °C. The farm experienced an outbreak of cryptosporidium between 2012 and 2014 and calf diphtheria was observed throughout this period. From 2014 antibiotic treatments were recorded in health records and from 2020 oral rehydration solution (ORS) use was also recorded.

All calves had their navels treated with iodine at birth and navels were checked daily until 14 days of age. Calves with a swollen navel, suspected umbilical infection or joint ill were isolated before antibiotic and non-steroidal anti-inflammatory (NSAID) treatment (Metacam [2.5 ml per 100 kg of LW s.c.]) or veterinary intervention if necessary.

Between 2014 and 2018, calves with scour were given 50 or 100g, depending on severity, of electrolyte (AsGold, Volac, UK), mixed with 2L of milk replacer. From 2020, calves with a faecal consistency score (FCS) of ≥2, according to the scale shown in Figure 4.3, were diagnosed with gastrointestinal enteric disorder (GED) and given a 60 g sachet of ORS (Osmofit, Trouw Nutrition, Ashbourne, Derbyshire), mixed with 2L of lukewarm water (25-35°C) and administered NSAID treatment.

Bovine respiratory disease (BRD) was diagnosed by visual signs in the first instance, including coughing, lethargy, drop in intake (MR only measurement), rapid respiration rate, snotty nose, sunken eyes, or droopy ears. However, droopy ears were also considered symptomatic of ear infections. Rectal temperature was recorded upon visual diagnosis of BRD or ear infection. Heifers with BRD or ear infection were treated with antibiotics and NSAID, followed 72 hrs later by a repeat NSAID treatment. Antibiotics for BRD included Betamox, Hexasol, Nuflor, Finadyne and Draxxin, however Draxxin (2.5 ml per 100 kg of LW s.c.) was most used.

2.3 Adult cow management

2.3.1 Cow housing and nutrition between 2007 and 2017

Following calving, all cows were moved to a pen in a freestall barn; each pen housed approximately 50 lactating cows. Pens were fitted with cantilever

cubicles, sawdust-covered rubber mattresses, an automatic slurry scraping system (CleanSweep, Dairymaster, Co. Kerry, Ireland) and an AMS (pre 2008: Merlin, Fullwood Ltd, UK; post 2008: Lely Astronaut A3, Lely Ltd., UK). Cows were dried off at approximately 60 days pre-calving and housed in a dry cow shed. At three weeks pre-calving, dry cows and heifers were moved to a straw-bedded calving pen in groups of 7 to 10 until calving.

Cows entered the AMS voluntarily and were dispensed a pelleted concentrate during milking, through an integral feed bin in the AMS. Concentrate allocation was based on individual milk yield and number of milkings per day. All lactating cows had *ad-libitum* access to a partial mixed ration (PMR) (Table 2.3), formulated to meet nutrient requirements for maintenance plus 27 to 30 L of milk production.

Table 2.3: Typical ingredients and composition of partial mixed ration offered to lactating cows between 2007 to 2018

	Partial mixed ration
Ingredients (g/kg dry matter):	
Grass silage	229
Maize silage	275
Whole crop silage	209
Wheat straw	9
Soyabean meal	84
Rapeseed meal	91
Molasses	27
Minerals	22
Fat supplement	19
Sugarbeet pulp	20
Soya hulls	7
Dried distiller's grains with solubles	7
Total	1000
Composition (% DM, except where shown)	
ME, MJ/kg DM	11.8
Dry matter	45.2
Crude protein	16.8
Crude oil	4.5
Crude fibre	-
Neutral-detergent fibre	35.5
Crude ash	7.5
Starch	15.3

Abbreviations: ME: metabolisable energy; MJ: megajoule; DM: dry matter

2.3.2 Cow housing and nutrition from 2018 onwards

Following calving, all cows were moved to a straw-bedded transition pen in the Nutrition barn until 7 to 10 days postpartum. Cows were then moved to other freestall pens which housed approximately 50 lactating cows. Unless requirements for a nutrition trial dictated otherwise, each pen contained an even spread of calving dates and parity to maintain constant demand on each AMS. Both the Nutrition and Flexible-housing barns were fitted with cantilever cubicles, deep sand beds, fully slatted flooring with underground slurry scraping, a robotic manure scraper (Lely Discovery 90 SW, Lely Ltd., UK) and AMS (Lely Astronaut A5; Lely Ltd., UK) that cows attended on average 3.0 to 3.5 times per day.

Table 2.4: Typical ingredients and composition of diet offered to lactating cows between October 2018 and June 2019

	PMR	AMS Concentrate
Ingredients (g/kg DM):		
Grass silage	229	-
Maize silage	275	-
Whole crop silage	209	-
Wheat straw	9	-
Soyabean meal	84	-
Rapeseed meal	91	-
Molasses	27	-
Fat supplement	19	-
Minerals	22	-
Sugarbeet pulp	20	-
Soya hulls	7	-
Dried distiller's grain with solubles	7	-
Composition (% DM, except where shown):		
ME, MJ/Kg DM	11.8	12.5
Dry matter	45.2	86.4
Crude protein	16.8	17.1
Neutral-detergent fibre	35.5	21.7
Crude ash	-	5.6
Starch	15.3	16.8
Sugar	-	7.0
Oil	4.5	4.3

Abbreviations: PMR: partial mixed ration; AMS concentrate: concentrate fed via automatic milking system during milking; ME: metabolisable energy; MJ: megajoule; DM: dry matter

Feeding consisted of PMR offered *ad libitum* and a concentrate individually fed in the AMS during milking according to milk yield (Table 2.4). The daily allowance of concentrate was calculated according to days in milk (DIM) until 70 DIM and according to milk yield after 70 DIM. Daily allowance was 2 kg/d on

day of calving, rising to 12 kg/d at 35 DIM, and remaining at 12 kg/d until 70 DIM. After 70 DIM, daily allowance was 3.5 kg/d plus 0.45 kg per L of daily milk yield between 32 and 51 L/d, averaged over the previous seven days. Daily concentrate allowance for each cow was divided across her expected number of milking visits. To avoid digestive upsets, concentrate allowance was limited to 12 kg/d and 3 kg per AMS visit.

For cows not on trial, PMR was mixed and dispensed with a complete diet mixer wagon (VM-2, Kongskilde Agriculture, Denmark). For cows on nutrition trials, PMR was mixed and dispensed with an automated feeding system (Pre 2018: Mix Feeder and Smart Feeder; Mullerup, Denmark. Post 2018: Mix and Carry Feeder; GEA Farm Technologies, Germany) and dispensed into feed bins daily. Cows had individual access (one cow at a time) to electronic feed bins (Pre 2018: Fullwood RIC feeders; Fullwood Ltd, UK. Post 2018: Hokofarm RIC feeders; Hokofarm, The Netherlands) containing PMR, and there were between 1.4 and 1.6 cows per feed bin. To ensure *ad libitum* feeding, PMR refusals were calculated daily and used to adjust quantities of PMR mixed to 110% of expected daily intake.

2.4 Heifer and cow reproduction

Heifer reproduction was managed by Genus plc who synchronised oestrus (Estrumate, MSD Animal Health UK Limited), identified heifers in oestrus by visual observation of bulling behaviour or disappearance of tail paint, and then artificially inseminated heifers.

Cows in oestrus were identified by farm staff and then artificially inseminated by Genus plc. Identification of cows in oestrus included visual observation of bulling behaviour and changes in cow activity measured by an electronic activity tag (Lely Qwes-H or Qwes-HR, Lely Industries BV, Maassluis, the Netherlands) on each cow's neck collar and alerted by herd management software (Uniform-Agri Professional, UK). The activity tag measured the frequency of electronic impulses in two hour intervals through changes in acceleration from head and neck movements.

Pregnancy diagnosis was confirmed by rectal palpation performed by the University of Nottingham School of Veterinary Medicine and Science. Bulls for artificial insemination were selected primarily for high yield of milk solids and profitable lifetime index, followed by low somatic cell count, good legs and feet, and wide rear teat placement. Sexed semen was used on all cows and heifers from 2016 onwards.

2.5 Data recording

Milking-related data were recorded by the cow management software (Time4Cows; T4C, Lely Ltd., UK) which was linked to the AMS in 2007. Mean milk yield, butter fat and protein between 2007 and 2021 was 10,477 L, 3.91% and 3.19%, respectively (Table 2.5). Historic lactating cow data were extracted via the Microsoft SQL Server Management Studio database linked to the T4C server and collated in Microsoft Office Excel (2016). Data relating to youngstock, fertility and herd exit were recorded by farm staff and uploaded to the herd management database (Uniform-Agri Professional, UK). These data were extracted from reports generated in Uniform and collated in Microsoft Office Excel (2016).

Table 2.5: Annual average milk yield, fat and protein between 2007 and 2021

Year	Milk yield, L	Milk fat, %	Milk protein, %
2007	9,969	4.12	3.36
2008	9,808	4.02	3.15
2009	10,025	3.92	3.13
2010	10,694	3.86	3.12
2011	11,248	3.82	3.15
2012	10,930	3.98	3.13
2013	9,867	4.03	3.13
2014	10,278	3.92	3.19
2015	10,458	3.79	3.24
2016	10,465	3.80	3.23
2017	10,465	3.81	3.22
2018	11,511	3.86	3.20
2019	12,777	3.94	3.18
2020	12,847	3.69	3.15
2021	11,398	4.12	3.14

No data was used from heifers that had been on other studies, except for heifers used in Chapter Four. Some cows were used in nutrition studies, typically lasting 3 months. Only 20% of the herd was on study at any one time, with one or two studies per year. Cows might participate in up to three studies in their lifetime, with 25 to 50% on control diets that were formulated to supply the same nutrients as the farm diet. No adjustment was made for time cows spent on study because this was a small percentage of their lifetime.

Chapter 3

Quantifying age at first calving

3.1 Introduction

Age at first calving (AFC) is a common key performance indicator (KPI) in the dairy industry. This is because it is easily measurable and requires no animal handling or equipment to record. For this reason, AFC has been studied extensively and has been found to affect many factors relating to herd performance.

The target of 730 days (24 months) at first calving is a long-standing recommendation in the UK. Benefits of an early AFC were recognised in the 1960s (Clark and Touchberry, 1962; Amir *et al.*, 1967) with 730 days (24 months) accepted as the optimum age to enter the milking herd by the 1990s (Hoffman and Funk, 1992; Heinrichs, 1993). However, many dairy producers worldwide do not achieve this target, with mean ages ranging from 745 to 943 days (24.5 to 31 months) (Ojango and Pollott, 2001; Haworth *et al.*, 2008; Brickell *et al.*, 2009c; Cole and Null, 2010; Wu *et al.*, 2012; Froidmont *et al.*, 2013). Mean AFC in the UK is 821 days (27 months) (Hanks and Kossaibati, 2020) and has not changed since 2015.

Heifers calving younger than 700 days (23 months) are thought to have compromised reproductive performance (Ettema and Santos, 2004) and reduced first lactation yield (Lohakare *et al.*, 2012). Heifers calving above 760 days (25 months) are thought to have reduced lifetime daily yield and herd longevity (Sawa *et al.*, 2019), poor udder health (Eastham, 2018), longer calving interval and poorer conception rate to first service (Ettema and Santos, 2004; Lohakare *et al.*, 2012). Therefore, it is widely accepted that optimal AFC for greater lifetime productivity, survivability, and fertility is between 700 and 760 days (23 and 25 months).

Studies have shown a positive relationship between AFC and rearing costs, as a lower AFC reduces the proportion of time a heifer is non-productive, and she begins repaying her rearing costs sooner. Boulton *et al.* (2017) found AFC to be a primary influence on variability of completed lactations, which ranged from 1.4 to 6.4, and calculated that it takes on average 530 days post-calving, or 1.5 lactations, for a heifer to pay back her rearing costs and return a profit to the

dairy unit. A later AFC incurs greater costs in additional days of housing, feeding and management, which amounts to £2.87 per cow for every one day increase in AFC (Boulton *et al.*, 2017). Therefore, reducing the current national average to 730 days (24 months) has the potential to decrease the financial costs of heifer rearing as well as reduce the number of herd replacements required (Garnsworthy, 2004).

Studies have shown that live weight (LW) and maturity of a heifer at calving are more important than AFC for achieving her potential milk production. Size of a heifer at calving is highly variable and can be affected by genetics, health, disease, diet, and nutrient utilization. Current recommendations suggest that a LW at first calving (LWFC) of 85 to 90% mature weight (MW) is appropriate for an AFC of 730 days (24 months) (Mourits *et al.*, 2000b; Gabler and Heinrichs, 2003; Margerison and Downey, 2005; Van Amburgh and Meyer, 2005). However, if producers achieve target AFC but not the correct LW due to inadequate daily LW gain (DLWG), then heifers calving too light will have reduced first lactation milk yield as energy for growth is diverted from milk production (Lohakare *et al.*, 2012). Additionally, there is the risk that after these heifers enter the herd, they will struggle to compete with mature cows. This could result in problems such as decreased feed intake and milk yield, and an increase in lameness events (Grant and Albright, 2001). On the other hand, if producers extend length of the rearing period to reach the target of 85 to 90% of MW without increasing DLWG, then increased AFC could negatively impact longevity and productivity (Cooke and Wathes, 2014).

Although recommendations for AFC and LWFC have existed for several years, many farms are still not achieving them. Duplessis *et al.* (2015)(Duplessis *et al.*, 2015) proposed that the disparity between recommended targets and actual AFC and LWFC is mainly due to inadequate DLWG, delayed age at first service (AFS) and underestimation of heifer weight at which first insemination should take place. Particularly in all-year-round calving (AYR) systems, where producers aren't tied to block calving, there is a temptation to increase length of the rearing period for heifers that are not considered big enough for insemination at 395 to 426 days (13 to 15 months), so producers delay first

insemination until heifers reach what they consider to be an ‘adequate’ size (Dingwell *et al.*, 2006). Producers also appear concerned about increased costs of feeding to achieve higher DLWG (Wathes *et al.*, 2014).

Researchers have questioned the validity of these AFC and LWFC recommendations, arguing that advantages of a younger AFC can be outweighed by the possibility of decreased milk yield per lactation and lower feed efficiency achieved by heifers that are still growing in first lactation (Hoffman *et al.*, 1996; Krpálková *et al.*, 2014a). There is also the argument that these recommendations, produced universally for the dairy industry, may be inappropriate to some farms' management systems and capabilities, with each dairy having a unique management strategy and environmental conditions (Wathes *et al.*, 2014).

This study aimed to quantify variation in age, LW and maturity at first calving to assess rearing efficiency and identify the proportion of Holstein-Friesian heifers achieving calving targets in a high-yielding, fully-housed, AYR system.

3.2 Materials and methods

3.2.1 Animals and location

This was a retrospective study carried out using data from Holstein-Friesian heifers born at the Nottingham University Dairy Centre between 2007 and 2018. Heifers were selected if they had a recorded date of first calving and had a recorded LW for the first 7 days post-calving (n=889).

3.2.2 Management

All heifers were fed and housed as described in 2.2 Youngstock management, and mated as described in 2.4 Heifer and cow reproduction.

3.2.3 Data collection

Microsoft SQL Server Management Studio was used to extract LW data which were measured using load cells fitted to the automatic milking system (AMS;

Lely Astronaut, Lely Ltd., UK) and recorded by T4C. LWFC was calculated as mean LW in the first 7 days post-calving. Mean herd MW for each year of birth was calculated as mean LW of cows in third lactation and above and between 100 to 200 days in milk. Mean herd MW was used to calculate 85% MW for individual cows. Season of birth and AFC were extracted from Uniform.

3.2.4 Statistical analysis

Data were collated using Microsoft Office Excel (2016) and analysed using GenStat (21st edition; VSN International, UK). Data for calving targets were grouped according to AFC; Early: <700 days (<23 months), Target: 700 to 760 days (23 to 25 months), Late: 761 to 851 days (25 to 28 months) and Very Late: >851 days (>28 months); and according to MW; Under: <85%, Target: 85 to 90% or Over: >90%. Season of birth was grouped according to; Spring (March, April, May), Summer (June, July, August), Autumn (September, October, November) and Winter (December, January, February). Data for AFC, LWFC and %MW at first calving were analysed using Residual Maximum Likelihood models with year of birth and season of birth as a fixed effect. Normal error distribution was used for LW and %MW data; Poisson error distribution with a log-linear link function was used for AFC. Data for achievement of calving targets and seasonal data were analysed using chi-square contingency tables. For variables with a dispersion parameter below 1, dispersion parameter was fixed at 1, and for variables with a dispersion parameter above 1, dispersion parameter was estimated. Data for AFC, LWFC and %MW at first calving were presented as medians with boxplots and Tukey whiskers. Means were presented as mean ± standard deviation (SD) and statistical significance was reported at $p<0.05$.

3.3 Results

3.3.1 Age at first calving

Distribution of AFC varied among years (Figure 3.1) and was positively skewed. Between 2007 and 2018 mean AFC was 757 ± 78 d, median AFC was 750 d, and AFC ranged from 557 days to 1071 days. Yearly mean ± SD AFC

ranged from 706 ± 58 days in 2008 to 813 ± 73 days in 2015 (p<0.001). Yearly median AFC ranged from 693 days in 2008 to 808 days in 2015.

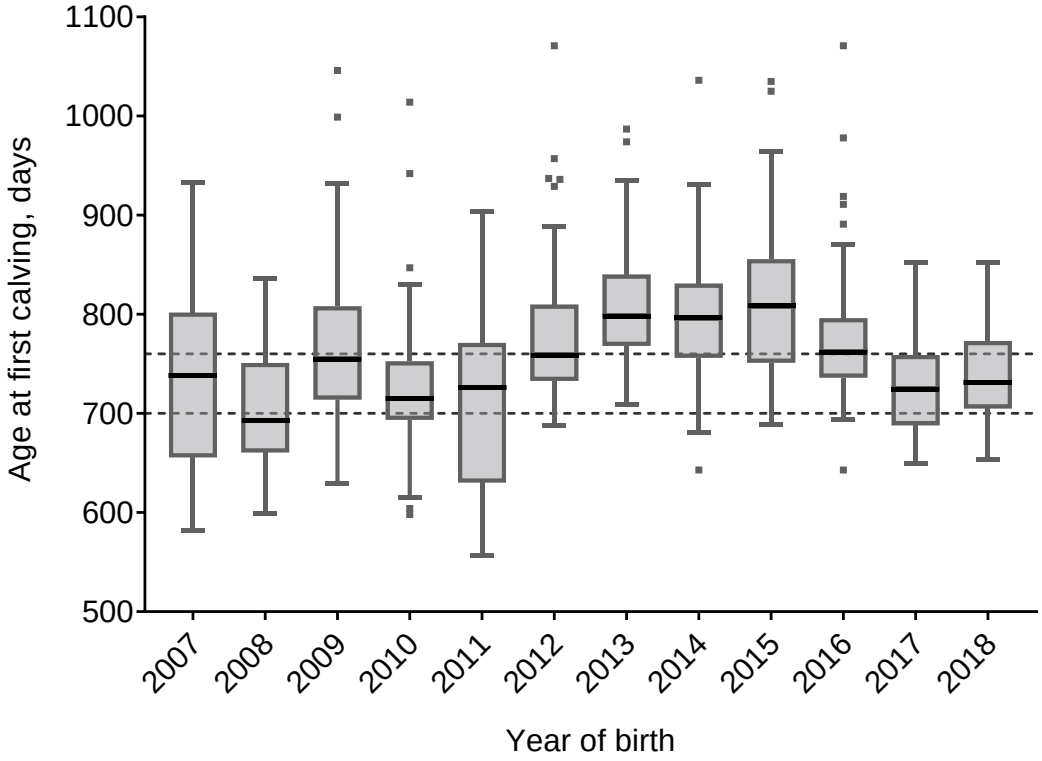


Figure 3.1: Variation in age at first calving by year of birth. The box bounds the interquartile range (IQR) divided by the median, and Tukey-style whiskers extend to a maximum of 1.5 × IQR beyond the box.
■ Data points beyond these upper and lower bounds are considered outliers
--- Dashed line represents industry calving target between 700 and 760 days (23 and 25 months)

3.3.2 Live weight and maturity

Distribution of LWFC is shown in Figure 3.2. Between 2007 and 2018 mean ± SD LWFC was 602 ± 69 kg and median LWFC was 604 kg, and LWFC ranged from 403 kg to 830 kg. Yearly mean ± SD LWFC ranged from 522 ± 61 in 2007

to 655 ± 55 in 2016 (p<0.001). Median LWFC ranged from 513 kg in 2007 to 657 kg in 2016.

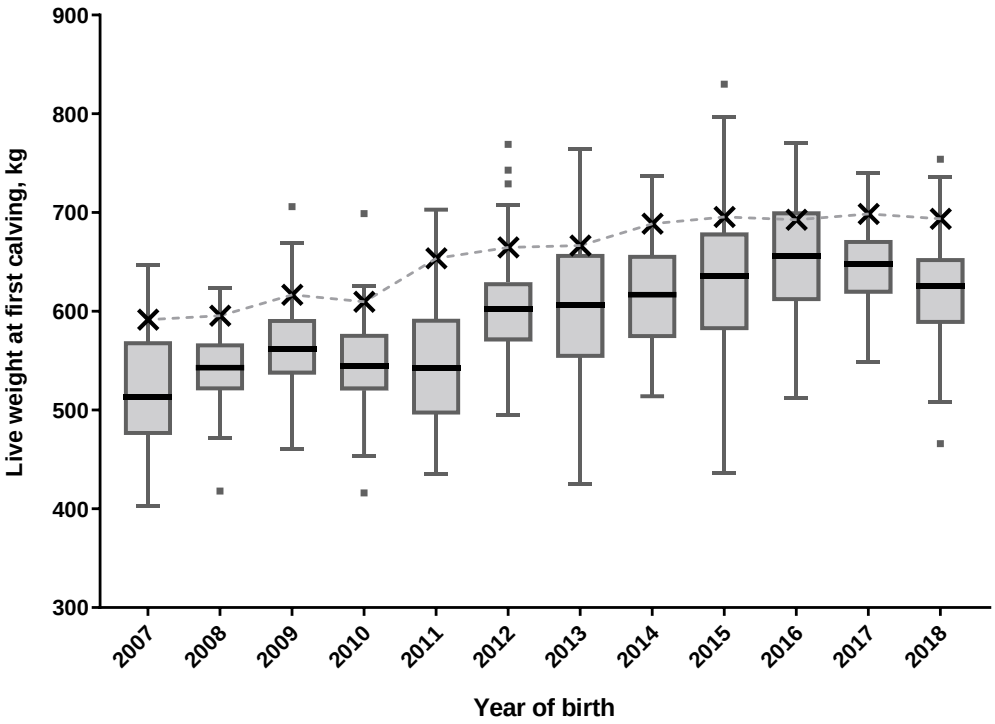


Figure 3.2: Variation in live weight at first calving by year of birth. The box bounds the interquartile range (IQR) divided by the median, and Tukey-style whiskers extend to a maximum of 1.5 × IQR beyond the box.
■ Data points beyond these upper and lower bounds are considered outliers
x Herd mature weight calculated as mean live weight of cows in third lactation and above and between 100 to 200 days in milk

Distribution of maturity is shown in Figure 3.3. Between 2007 and 2018, the mean ± SD % MW was 87.5 ± 8.5% and median was 87.3%, and % MW ranged from 60.7% to 115.5%. Yearly mean ± SD ranged from 81.4% ± 9.2% in 2011 to 91.5% ± 7.7% in 2016 (p<0.001). Yearly median % MW ranged from 80.3% in 2011 to 91.7% in 2016.

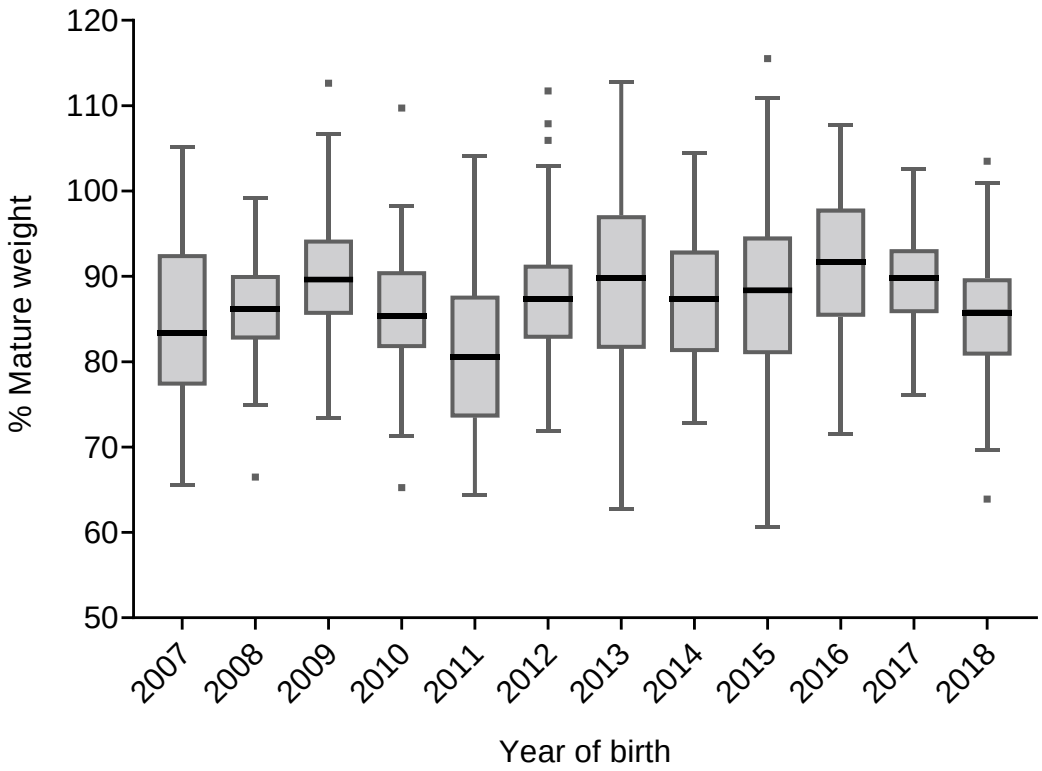


Figure 3.3: Variation in maturity at first calving by year of birth. The box bounds the interquartile range (IQR) divided by the median, and Tukey-style whiskers extend to a maximum of 1.5 × IQR beyond the box.

- Data points beyond these upper and lower bounds are considered outliers

3.3.3 Calving targets

Of 889 heifers that calved, 35.7% (n=317) calved within the target age range of 700 to 760 days (Figure 3.4a), 23.3% (n=207) calved within the target maturity range of 85 to 90% MW (Figure 3.4b), and 10.0% (n=89) calved within both targets (Figure 3.4c). Achievement of targets fluctuated between 2007 to 2013, but the proportion of heifers that achieved both targets increased steadily from 2014 (

Table 3.1).

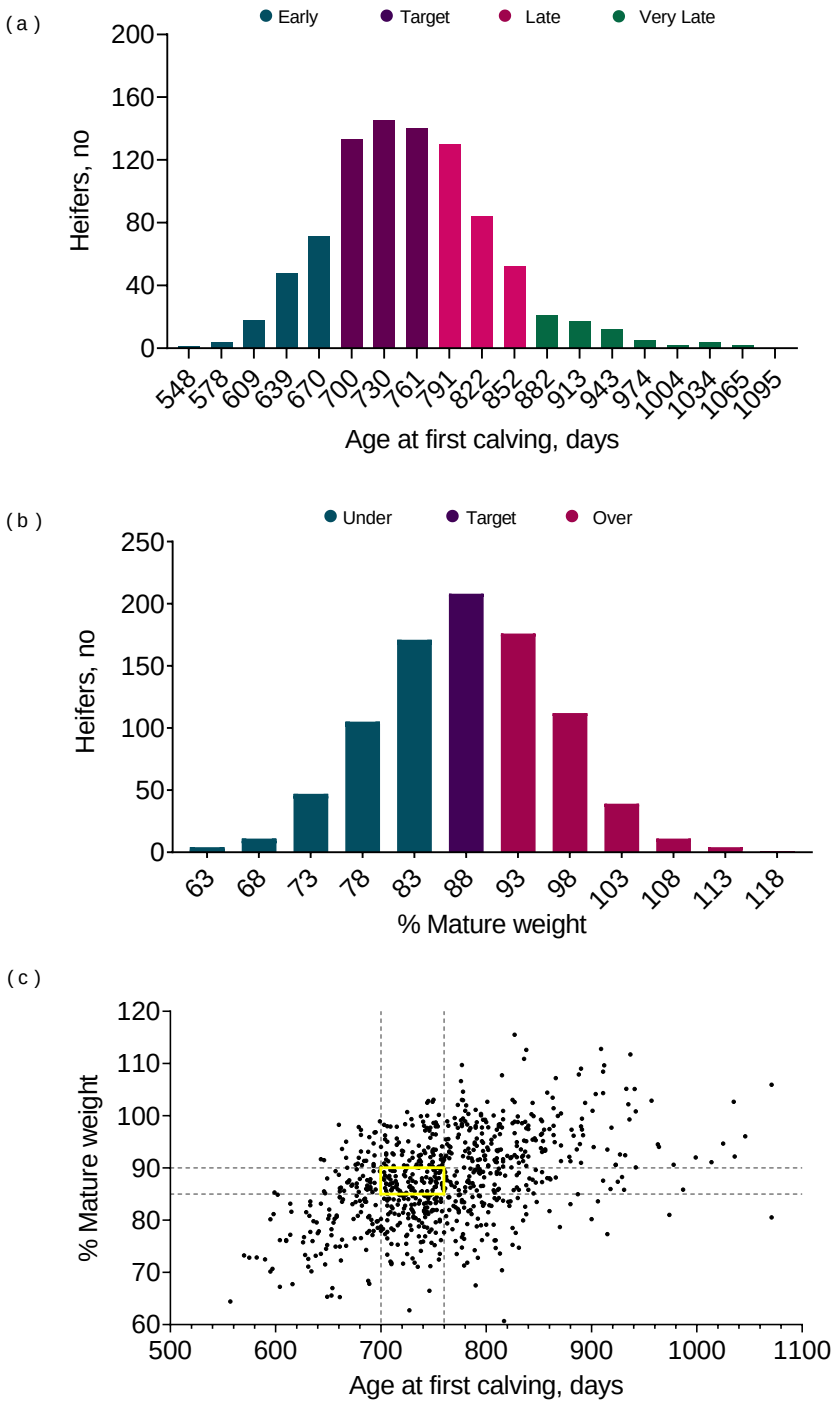


Figure 3.4: Distribution of (a) age at first calving, (b) maturity at first calving and (c) relationship between age and maturity at first calving.
- - - Target range for maturity (85 – 90%) and calving age (700 – 760 days)

☐ Animals within maturity and calving age targets

Table 3.1: Proportion of heifers achieving calving targets from 889 heifers born between 2007 and 2018

Year of birth	No. of heifers	% Achieved AFC target	% Achieved MW target	% Achieved both targets
2007	54	13.0	11.1	0.0
2008	41	29.3	39.0	9.8
2009	67	40.3	28.4	14.9
2010	57	54.4	26.3	19.3
2011	58	25.9	15.5	6.9
2012	74	48.6	27.0	13.5
2013	67	19.4	14.9	4.5
2014	63	23.8	22.2	3.2
2015	88	30.7	18.2	5.7
2016	89	44.9	14.6	4.5
2017	91	41.8	27.5	11.0
2018	140	40.0	31.4	18.6

Abbreviations: AFC, age at first calving; MW, mature weight

3.3.4 Season

Seasonal distribution of calvings varied each year (Table 3.2) and there was a difference between seasonal means (Pearson chi-square value = 67.31 with 33 d.f., $p<0.001$). Number of heifer calves born each year increased from 54 in 2007 to 140 in 2018. Season of birth affected AFC ($p=0.003$), with heifers born in autumn and winter calving the earliest (748 days), followed by spring (758 days) and lastly summer (767 days).

Table 3.2: Seasonal distribution of calvings between 2007 and 2018 in 889 heifers that survived to first calving

Year of birth	Season of birth				Total calvings
	Spring	Summer	Autumn	Winter	
2007	14	14	16	10	54
2008	11	17	8	5	41
2009	21	14	17	15	67
2010	16	18	8	15	57
2011	13	20	10	15	58
2012	18	28	7	21	74
2013	13	19	16	19	67
2014	8	28	16	11	63
2015	16	17	32	23	88
2016	13	21	26	29	89
2017	26	25	15	25	91
2018	39	21	40	40	140
Total	208	242	211	228	889

3.4 Discussion

3.4.1 Age at first calving

In this herd, mean AFC for the study period was 757 days (24.9 months), which was towards the upper end of the 700 to 760 days (23 to 25 months) target but lower than the UK average of 821 days (27 months) (Hanks and Kossaibati, 2020). AFC was distributed over 514 days (16.9 months), ranging between 557 to 1071 days (18.3 to 35.2 months), with only 35.7% of heifers calving between 700 to 760 days (23 to 25 months). This range is similar to previous studies which found AFC varied as much as 334 days (11.1 months) (Boulton *et al.*, 2017) to 895 days (29.7 months) (Brickell and Wathes, 2011; Foskolos and Moorby, 2016). However, variation in AFC decreased in the last two years of the current study, which may be because animals moved into new accommodation in 2017, allowing better management across the herd.

With 43% of all heifers in this study not calving until after 760 d, the high variability in AFC is largely the result of a long tail of older heifers. Several explanations for a positively skewed AFC need to be identified on an individual herd basis. There may be differences in AFS due to delayed mating of heifers that are not considered sufficiently mature at 456 days (15 months) (Dingwell *et al.*, 2006). Insufficient maturity may be due to compromised growth during rearing, due to incidence of disease (Donovan *et al.*, 1998b) or poor fertility (Wathes *et al.*, 2014). Alternatively, it may be a producer's choice to delay calving due to feed costs and availability. However, in an indoor housed system, such as researched in the current study, variation due to quality and availability of feed should be lower than in a grazing system. It is possible, therefore, that a combination of factors could have affected age at conception and subsequent AFC in this study.

3.4.2 Live weight and maturity at first calving

LW and maturity at first calving varied considerably in the current study. Yearly mean LWFC increased by 100 kg between 2007 and 2018, which could be due to genetics if selecting for higher milk yields resulted in bigger animals. This is

because bulls were selected for higher milk solids yield, therefore LWFC was expected to increase over the study period. Animal size needs to be considered when setting LW targets. Using breed recommendations of 550 to 650 kg at first calving for pedigree Holsteins (Smith, 2007; AHDB, 2020), 54% of heifers in this study would have been regarded as suitable weight according to breed recommendations. This approach may be appropriate for herds where there is a large variation in size, and the producer cannot facilitate weighing animals. However, with 46% of heifers in the current study varying greatly from breed standards, it is perhaps more important to suggest LW targets based on individual herd performance, especially with regard to modern breeding policies and production systems (Bach and Ahedo, 2008).

LWFC targets also do not take into consideration a heifer's physiological development in relation to final mature size and composition (Freetly *et al.*, 2001), or an increasing herd MW. Using a maturity target of 85 to 90% MW (Margerison and Downey, 2005), only 23% of heifer LW were regarded as optimum at first calving, with almost equal proportions of heifers regarded as either underweight (38%) or overweight (39%). The proportion of heifers achieving MW target may be low due to a narrower target range, however, targets based on herd MW may be seen as more accurate and give a truer reflection of calving performance. Lighter animals may also be seen as less mature, but they may simply be smaller in stature. This needs to be considered when selecting a bull for calving ease. Nevertheless, targets and calculations based on herd MW favour systems with the means to weigh growing heifers and adult cows. Therefore, it is also important to explore alternative calving targets and methods of measuring heifer growth to improve recording of heifer data on commercial farms.

Farm policy at CDSI changed in 2012 from calving at 730 days (24 months) to 760 days (25 months), due to younger calving heifers exhibiting poor performance and struggling to compete in the herd. As only 28% of heifers calving at target age were also of optimum maturity, this suggests that heifers were the correct age but not LW, which is more likely to be the reason for poor performance than young calving age alone. Heifers calving too light may have

a lower first lactation yield and increased competition for feed, water and space due to smaller body size (Munksgaard *et al.*, 2020). To reduce competition and small heifers entering the herd, heifers should be grown so that they calve with sufficient maturity. However, the current study also showed that there was an almost equal proportion of overweight heifers at calving. Excess body condition should be avoided to prevent reduced fertility and lower lifetime yields (Mee, 2008a). Heifers that were overweight at calving were those calving late. Therefore, reducing the long tail of older heifers should reduce the proportion of heifers calving overweight.

Heifers were not weighed in this herd; therefore growth rate was not monitored and heifers were bred according to age and visual estimation of LW. A study by Dingwell *et al.* (2006) found that vets and farmers misjudged LW of heifers in 81% of their attempts, often by as much as 97 kg, which could explain the variation in LWFC. Surveys have highlighted that many farmers felt that measuring with a weigh scale was impractical on-farm, requiring excessive amounts of time and investment (Heinrichs *et al.*, 1992; Heinrichs *et al.*, 2007). However, the wide variation in LWFC suggests that to record growth rate accurately and determine correct mating size, more efficient methods of weighing and/or measuring heifer development, which are easy to implement and quick to use, need to be developed. These methods should include measurements at weaning, first service, and calving.

3.4.3 Season

In this AYR calving system, heifers born in autumn and winter calved earliest at 748 days. This is 19 days younger than heifers born in summer. At first, this seems unexpected as lower temperatures and humidity, particularly in winter, might negatively impact heifer health and growth which may delay AFC. However, this confounding outcome is consistent with Chester-Jones *et al.* (2017) who found that heifers born in winter had higher growth rate. Improvements in heifer housing to better control environmental temperature could be required. Similarly, Bell *et al.* (2021) suggests using hours below lower critical temperature rather than average environmental temperature when

comparing growth rates. This could not be included in the current study and warrants further exploration.

3.5 Conclusion

Variation exists in the dairy industry due to differences in animal biology, farm systems, and farm management. High variation in AFC and LWFC increases management challenges and reduces heifer rearing efficiency. Targets and KPIs are useful for producers to work towards economic and productive gains, although means within target recommendations can hide inefficiencies in dairy systems. Mean AFC masks the long tail of older heifers, which adds to greater rearing costs, reduced efficiency, and management challenges. The proportion of heifers achieving target AFC was low in the current study, which should be considered when evaluating heifer rearing efficiency and targets. Assessment of factors contributing to a later AFC is recommended. Ultimately, it is important for producers to look beyond performance means and targets, and to identify causes of variation in AFC and LWFC on an individual herd basis to improve efficiency of the whole system.

Chapter 4

Gastrointestinal enteric disorders and early life performance

4.1 Introduction

Calves are at greatest risk of death during their first 21 days of life (Waltner-Toews *et al.*, 1986c; Wells *et al.*, 1997), making the pre-weaning phase a critical period in heifer rearing. Gastrointestinal enteric disorder (GED), resulting in scour, is most prevalent at this age, therefore early diagnosis of disease is vital. Causes can be nutritional, causing osmotic scour, or infectious, such as pathogens of viral, bacterial, or parasitic origins, causing secretory or malabsorptive scour (Stoltenow and Vincent, 2003). Leading pathogenic sources are rotavirus, coronavirus, *Escherichia coli*, *Clostridium perfringens*, *Salmonella spp., Cryptosporidium parvum and Coccidiosis*, which attack the gastrointestinal tract (GIT) lining and decrease the calf's ability to absorb essential nutrients from milk (Constable, 2004; Taylor *et al.*, 2010). Sources cannot be identified through visual presentation only, so in most cases, calves are given oral rehydration and pain relief. However, if diagnostics confirm a bacterial source, antibiotic treatment can be prescribed (Potter *et al.*, 2012), and severe cases may require veterinary intervention for intravenous fluid therapy (Berchtold, 2009). To reduce the severity and incidence of scour, common practices include good colostrum management and hygiene.

In the UK, little is known about GED incidence. It is estimated that over a third of calves are affected by scour to varying degrees during their rearing period, and average incidences of scour in other countries, including the USA, Canada, Holland, and Sweden were between 10 and 25% (Johnson *et al.*, 2011). Scour costs the UK cattle industry an estimated £11 million each year in antibiotics, milk replacer (MR) and oral rehydration (AHDB, 2013). Scour in early life can also increase the calf's susceptibly to subsequent disease (Curtis *et al.*, 1988; van der Fels-Klerx *et al.*, 2001; Hultgren *et al.*, 2008), which further adds to morbidity rates, rearing costs, and reduces performance in many dairy herds by reducing growth (Virtala *et al.*, 1996c; Windeyer *et al.*, 2014) and delaying AFC (Waltner-Toews *et al.*, 1986b).

A challenge with GED is that damage to the GIT has already occurred by the time a calf presents scour. Therefore, early detection is essential to reduce GIT

damage and dehydration. Automated feeding systems should be optimised to develop measures which can be easily incorporated into remote and reliable monitoring of calf health to predict subclinical disease (Svensson and Jensen, 2007; Swartz *et al.*, 2017; Cramer *et al.*, 2020). Recent studies have associated milk feeding behaviours with pre and post clinical signs of disease. Reduction in milk intake has been observed before disease presentation (Lowe *et al.*, 2019), and reduced drinking speed and fewer automatic calf feeder (ACF) visits are associated with calves diagnosed with disease (Svensson and Jensen, 2007; Sutherland *et al.*, 2018).

The current study aimed to evaluate effects of GED in early calfhood on individual feed intake behaviour, growth rate, and live weight (LW) at weaning. The hypothesis was that calves treated for GED have reduced feed intake, growth rate and weaning LW.

4.2 Material and Methods

4.2.1 Animals and location

This study was conducted at the Centre of Dairy Science and Innovation using 53 Holstein-Friesian heifer calves born between October 2020 and June 2021. All calves were inspected for suitability and signed onto the study by the Named Veterinary Surgeon (or Deputy) at 4 (± 3) days of age. At 84 (± 3) days all calves were signed off the study and returned to the herd.

4.2.2 Housing and nutrition

All calves followed the newborn calf protocol after birth, as described in 2.2 Youngstock management.

Following three meals of transition milk, calves were offered 4 L of energised MR (50% skimmed-based; Milkivit Energizer, Trouw Nutrition, UK) for the fourth and fifth meals via slow-flow teat buckets. MR was offered following manufacturer's recommendations: MR mixed with water at 42°C at a concentration of 135 g/L and fed to calves at 38°C. At 4 days of age, calves were fitted with a radio-frequency identification tag and registered to a milk

feeding station operated by an ACF (VARIO smart, Förster-Technik, Germany), which would dispense the sixth and subsequent MR meals. When a calf presented itself at the milk feeding station, the ACF would mix an individual portion of MR and dispense the calf its MR allowance. The calf's daily MR allowance was calculated by the ACF, according to a 67-d feed curve (Figure 4.1) for step-down weaning by 70 days of age. Each pen had *ad-libitum access* to two 8 L buckets of fresh clean water from birth, and to a texturized starter concentrate (Calf Course Mix, Irwin Feeds, UK) and chopped cereal straw suspended in individual feeders (JFC Ltd, UK), from 7 days of age to 14 (± 3) days post-weaning (Table 4.1).

Table 4.1: Composition of milk replacer, starter concentrate and straw offered to heifers between birth and 84 days of age

Composition (% DM, except where shown)	Milk replacer[1]	Starter concentrate	Straw
ME, MJ/kg DM	21.0	12.0	4.0
Dry matter	96.8	87.3	91.4
Crude protein	22.5	18.5	5.3
Crude oils and fats	25.0	4.1	1.9
Crude fibre	0.02	4.6	33.9
Neutral-detergent fibre	-	-	8.1
Crude ash	7.0	5.1	6.8

[1] Milk replacer ingredients: skimmed-milk powder, refined vegetable oil (palm, coconut), whey powder, whey powder protein, calcium carbonate, calcium butyrate

Abbreviations: DM, dry matter; ME, metabolisable energy; MJ, megajoule

Immediately after birth, calves were transferred to the calf-rearing unit. The unit was divided into two interconnected umbrella-span sheds with separate ventilation systems so that air space was not shared between sheds. Each shed consisted of two straw-bedded areas (13.5m x 3.5m), each fitted with nine feeding stations operated by an ACF (VARIO smart, Förster-Technik, Germany). Movable PVC panels were used to partition nine smaller pens (1.5m x 3.5m) to house calves in pairs with one feeding station per pen. Calves remained with their pen mate from birth to 14 (± 3) days post-weaning unless isolated and treated due to ill health as required by the Named Veterinary Surgeon (or Deputy). After weaning, pairs of calves were moved into a group

calf pen until group size reached 16 calves, when the whole group was moved to a heifer rearing shed.

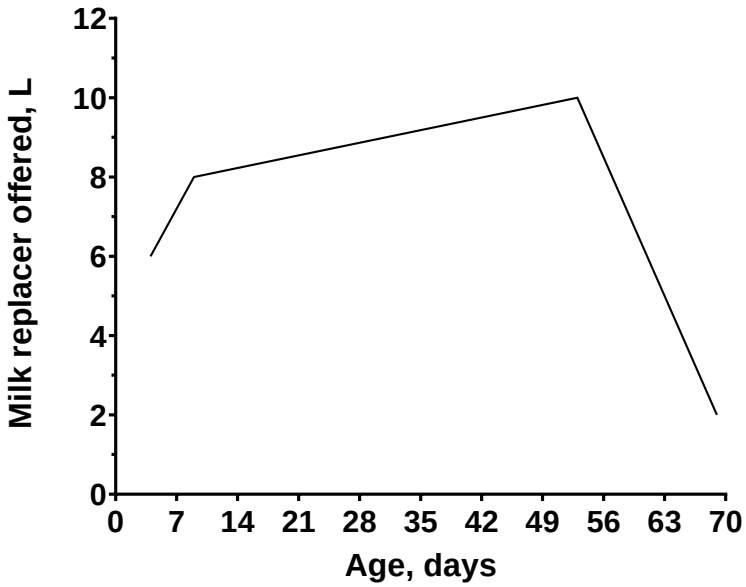


Figure 4.1: Feed curve programmed for step-down weaning at 70 days of age: 6 L in 2 L allowances at 4 days of age; 8 L in 2 – 3 L allowances at 13 days of age; 10 L in 3.5 – 4 L allowances at 53 days of age reducing to 2 L at 69 days of age

4.2.3 Calf health

All calves were vaccinated against bovine respiratory disease (BRD; Rispoval RS+Pi3 IntraNasal; Zoetis) at 9 days of age and all oral rehydration solution (ORS) and treatments were recorded in the youngstock health dairy. Temperature and humidity were recorded daily throughout the study (Figure 4.2) and calf jackets were routinely used when ambient temperature fell below 15 °C.

All calves had their navel treated with iodine at birth and were then checked daily until 14 days of age. Calves with a swollen navel, suspected umbilical infection or joint ill were given antibiotic and a non-steroidal anti-inflammatory (NSAID) treatment (Metacam [2.5 ml per 100 kg of LW s.c.]), with veterinary intervention if necessary.

Calves with a faecal consistency score (FCS) of ≥2 were diagnosed with GED and given a 60 g sachet of ORS (Osmofit, Trouw Nutrition, UK), mixed with 2 L of lukewarm water (25 °C to 35 °C) and administered NSAID treatment (Metacam [2.5 ml per 100 kg of LW s.c.]).

Clinical symptoms of BRD included coughing, lethargy, drop in MR intake, rapid respiration rate, snotty nose, sunken eyes, or droopy ears. However, droopy ears were also considered symptomatic of ear infection. Rectal temperature was recorded upon visual diagnosis of BRD or ear infection. Calves with BRD or ear infection were inspected by the Named Veterinary Surgeon (or Deputy) and were given antibiotics (Draxxin [2.5 ml per 100 kg of LW s.c.]) and NSAID (Metacam [2.5 ml per 100 kg of LW s.c.]), followed 72 hrs later by a repeat NSAID treatment if symptoms were moderate, or just NSAID treatment if symptoms were mild. All sick calves were monitored twice daily, and rectal temperature was recorded until symptoms cleared.

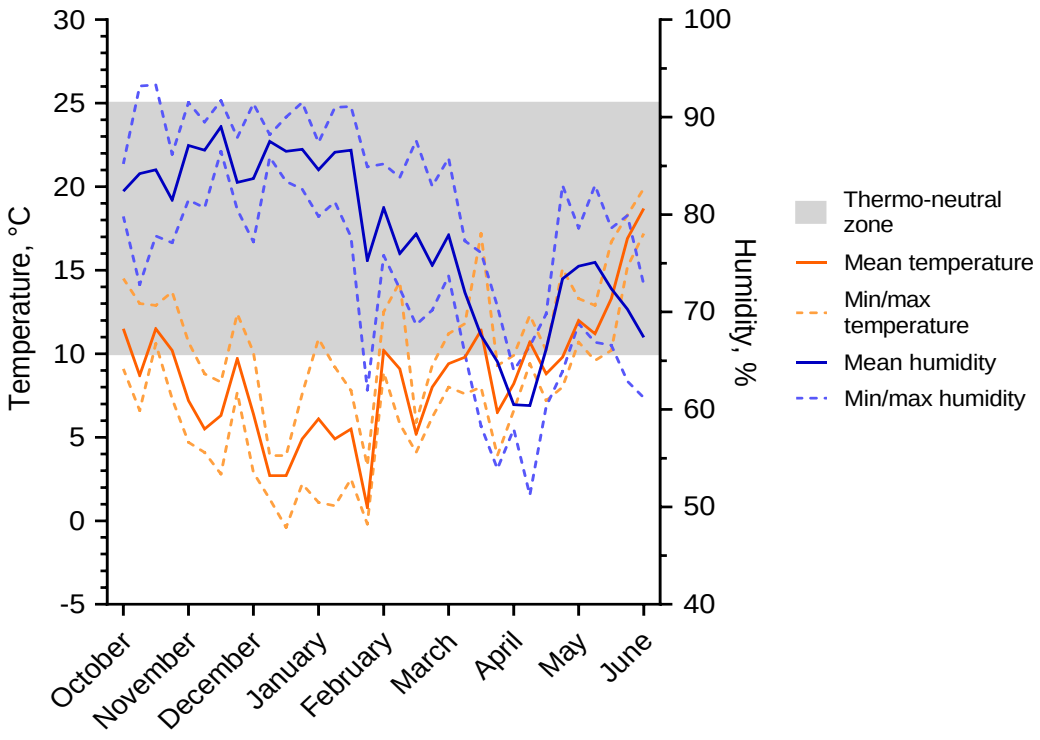


Figure 4.2: Minimum, maximum, and mean temperature and humidity inside the calf-rearing unit between October 2020 and June 2021

4.2.4 Measurements

4.2.4.1 Faecal consistency scoring

Faecal consistency of all calves was scored daily using a 4-point scale as described by McGuirk (2008), in which 0 was normal and 3 was watery faeces (Figure 4.3). FCS was recorded and accumulated to give a total FCS between

birth and 84 ± 3 days of age. Treatment and number of days with FCS >0 were recorded.

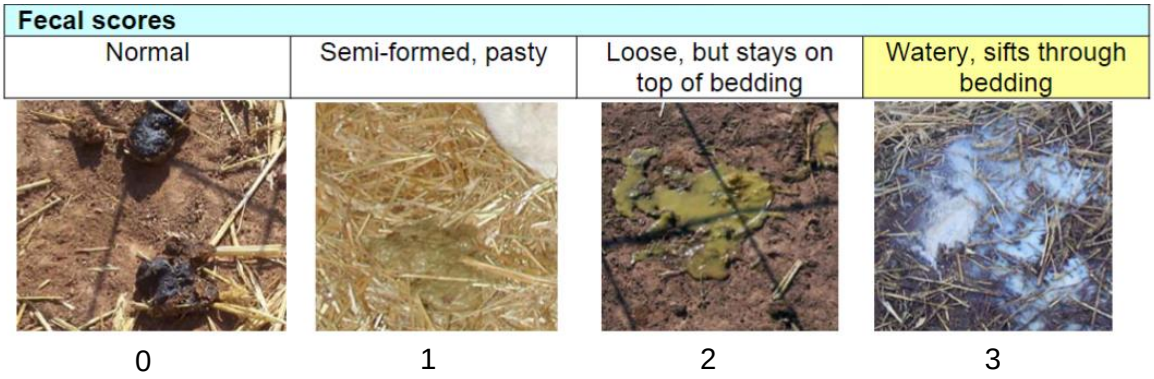


Figure 4.3: Visual scale of faecal consistency with scores indicating the following: 0 = normal, 1 = semi-formed, 2 = loose and 3 = watery. A faecal consistency score ≥ 2 indicates gastrointestinal enteric disorder. (Taken from the Wisconsin Calf Health Score Chart based on McGuirk, (2008))

4.2.4.2 Live weight, daily live-weight gain, and stature

All calves were weighed with high capacity platform scales (Salter Brecknell PS1000, Brecknell, UK) directly following entry into the calf facility to record birthweight. LW of each calf was then recorded daily using electronic load cells fitted to the feeding station at each ACF and reported as a smoothed weekly mean. Mean daily LW gain (DLWG) was calculated over the pre-weaning (0 to 70 days), post-weaning (70 to 84 days) and whole rearing period (0 to 84 days). Stature was recorded at 0, 7, 14, 28, 56, 70 and 84 (± 3) days of age, by measuring hip width, using a 1000 mm digital vernier calliper (CR2032, Arc Euro Trade, UK), and hip height with a 180 cm measuring stick (Lincoln measuring stick, Battles, UK). A wooden board was used to provide a flat surface for heifers to stand on whilst measuring hip height.

4.2.4.3 Feed intake, composition, and efficiency

Daily allowance and intake of MR for individual calves were extracted from the CalfCloud database linked to the ACF and used to calculate weekly mean and total MR (L and kg) intake. Starter concentrate and straw refusals for each pen were measured twice a week by placing feeders on an electronic weigh scale and subtracting feeder weight (starter concentrate feeder: 12.70 ± 0.05 kg, straw feeder: 11.13 ± 0.01 kg) from total weight. Feed refused was removed

from the feeder after weighing and replaced by fresh feed that was weighed and recorded. Daily feed intake per pen was calculated as the difference between feed offered and feed refused divided by number of days between measurements. Pen intake was divided by two to estimate individual feed intake. Daily intakes of concentrate and straw were used to calculate accumulated intakes per calf. Pen water intake was measured once a week by calculating the difference between water offered and refused over a 24-hr period.

Samples (500 g) of MR, starter concentrate, and straw were collected weekly and frozen at -20 °C until analysis for DM, crude protein, crude oil, crude fibre, NDF and ash (AOAC, 1990). Cumulated fresh intake and DM intake (DMI) of MR, starter concentrate, and straw were used to calculate feed conversion ratio (FCR; DMI, kg/ live-weight gain, kg).

4.2.4.4 Milk feeding behaviour

Milk feeding behaviours [MR intake (mL/d), drinking speed (mL/min), feeding duration (min), breakoffs, rewarded visits, unrewarded visits, and total visits per day] were recorded by ACF throughout the pre-weaning period. A breakoff was defined as when the calf stopped drinking before full milk allocation was consumed (Jorgensen *et al.*, 2017). Milk feeding visits were described as either rewarded or unrewarded depending on whether the calf had a milk allowance available or not when entering the ACF. Feeding behaviour data were downloaded from CalfCloud and collated in Microsoft Office Excel (2016). MR intake and visit data were summed to provide a total amount for each day. Drinking speed from each visit during each feeding day was averaged to provide one daily value for drinking speed.

4.2.5 Statistical analysis

Data were collated using Microsoft Office Excel (2016) and analysed using GenStat (21st edition; VSN International, UK). Calves were grouped according to whether they had no incidence of GED (0 GED: FCS 0 or 1) or at least one incidence of GED (+ GED: FCS 2 or 3). Data for growth and stature (DLWG,

LW, hip height and hip width), feed intakes (daily and accumulated intakes of MR, water, starter concentrate and straw) and milking feeding behaviours (rewarded, unrewarded and total visits, breakoffs and drinking speed) were analysed using residual maximum likelihood (REML) models, where fixed effects were GED group (0 GED or + GED) and week of life, and random effect was individual calf. Week of life was entered into the model as a factor to examine differences over the pre-weaning period. REML was also used to analyse MR intake from days 4 to 53 (peak MR allowance), using GED group, age and age^2 as fixed effects, and individual calf as random effect. Age (days) was entered into the model as both a linear and quadratic component to examine if there was quadratic relationship between age and GED. Data at three timepoints [weeks 4, 10 (weaning) and 12] were analysed using generalised linear models (GLM) with GED group as fixed effect. For variables with a dispersion parameter below 1, dispersion parameter was fixed at 1, and for variables with a dispersion parameter above 1, dispersion parameter was estimated. Gompertz nonlinear regression model was used to describe growth curves in 0 GED and + GED calves from weeks 1 to 12. The fitted curve was described as:

*A + C*EXP (-EXP (-B* (X-M))),*

where A was a scaling factor and represented asymptotic LW which shifted the growth curve vertically; C was a linear factor and the intercept which altered starting LW; B was a non-linear factor and the point of inflection which represented maximum rate of growth; and M was a non-linear factor and moved the point of inflection horizontally. A scaling factor was defined as the ratio between the scale of a given original curve and a new curve.

Statistical significance is reported at $p<0.05$ using a confidence interval of 95%. Tabulated means are presented with their standard error, and statistical insignificance is reported as NS. Data presented in figures are assigned ∗ for $p<0.05$, ∗∗ for $p<0.01$ and ∗∗∗ for $p<0.001$.

4.3 Results

4.3.1 Disease prevalence and treatment

A total of 53 calves were observed between 0 and 84 ± 3 days of age, of which 23 were diagnosed with GED (FCS≥2) and 19 received treatment for respiratory symptoms (Figure 4.4). There were 7 calves treated for 'off milk', which was the term given when a calf was reluctant to drink but had no visual clinical symptoms, and 6 calves treated for 'other' reasons. These reasons included: bloodshot eyes, blood in faeces, stuck under raceway, jaw abscess, drawn-out and precautionary respiratory concern. Ear infection was determined by droopy ears with no other clinical symptoms and was observed in 4 calves. No calf had swollen navel or navel infection. Similar numbers of calves with (n=11) and without (n=8) GED were treated for respiratory symptoms.

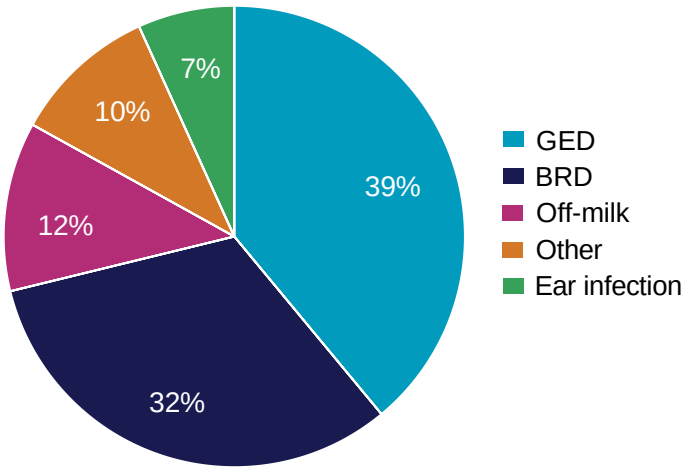


Figure 4.4: Causes of morbidity between birth and 84 days of age in Holstein-Friesian heifer calves born (n=53) between October 2020 and June 2021. Abbreviations: GED, gastrointestinal enteric disorder; BRD, bovine respiratory disease

There were 89 incidences of abnormal faecal consistency (FCS>0) among 40 calves throughout the study period (Figure 4.5a), of which 17 calves had semi-formed faeces (FCS=1), 18 had runny faeces (FCS=2) and 5 had watery faeces (FCS=3). There were 41 incidences of GED (FCS≥2) among 23 calves, of which 97% were before 28 days of age. Of the 23 calves with GED; two were individually housed, 13 were one calf in a pair and 8 were both calves in a pair (i.e., four pairs). Median age of calves with GED was 14 days (IQR: 10 to 15

days), and GED calves scoured on average for 1.8 +/- 1.5 days. Days scouring were: 1 day (n=13), 2 days (n=5), 3 days (n=2) and 4 days (n=3). Of the 30 calves that were not diagnosed with GED, 13 had normal faecal consistency (FCS=0), of which only 5 had no incidence of disease in the first 12 weeks of life. Mean accumulated FCS between birth and 12 weeks of age in calves without GED was 0.9 (range: 0 to 5) and with GED was 4.8 (range: 2 to 10). There were 41 treatments for BRD given to 19 calves between the ages of 21 and 78 days (Figure 4.5b). Median age of calves treated for respiratory symptoms was 54 days (IQR: 44 to 66 days).

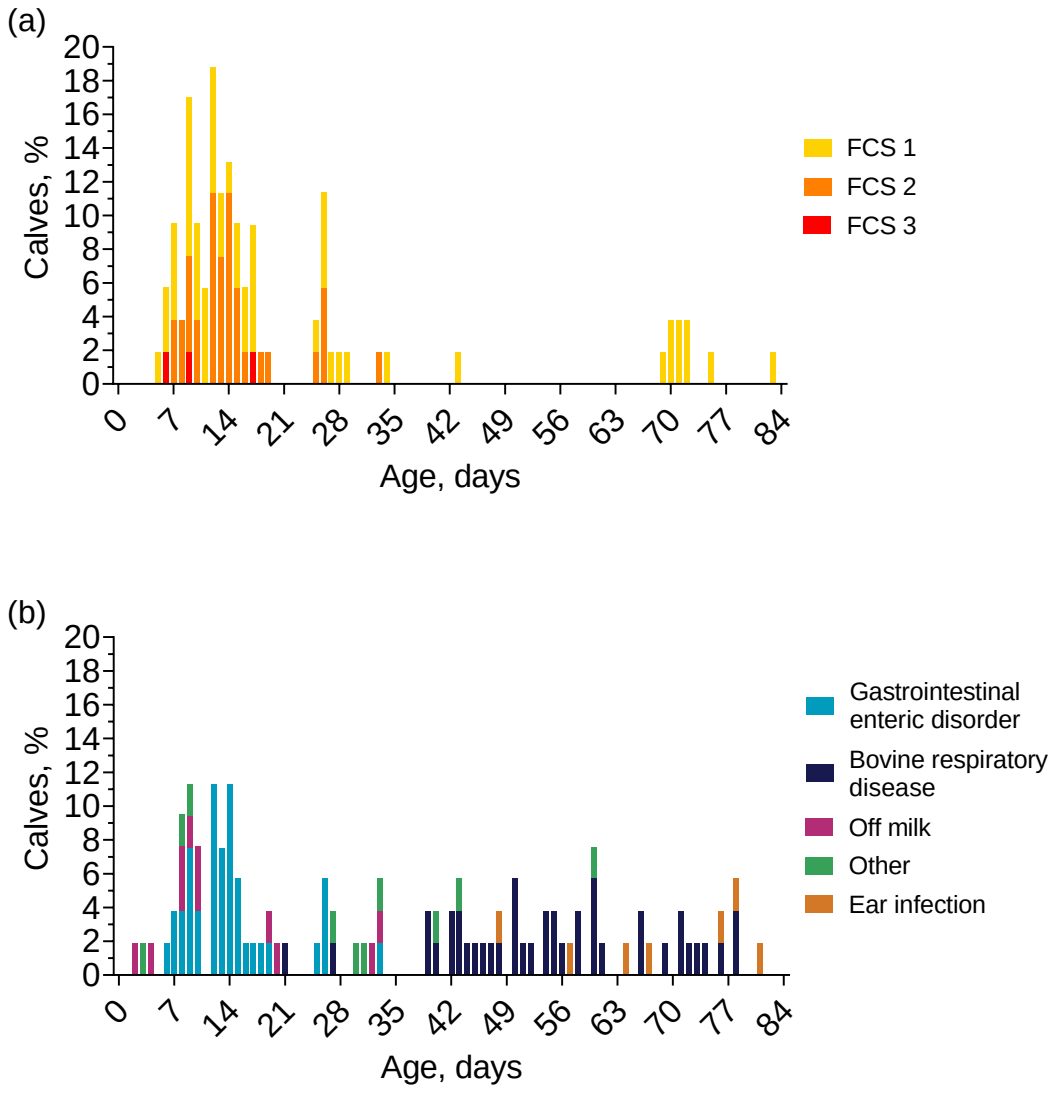


Figure 4.5: Age distribution of (a) faecal consistency score (FCS) and (b) ill health between birth and 84 days as a proportion of total Holstein-Friesian heifer calves born between October 2020 and June 2021 (n=53)

4.3.2 Live weight, daily gain, and stature

Calves with GED weighed less at birth than calves without GED, but this was not significant (p=0.056). All other growth parameters for each time point were significant except hip width at week 4 (Table 4.2). Linear and quadratic components in the model were significant for age interactions (p<0.001), however, only linear components were significant for age*GED interactions (p=0.013), indicating that GED did not affect the non-constant rate of growth. Both groups took until week 4 to achieve a DLWG of 0.80 kg/d and then maintained DLWG between 0.80 and 1.19 kg/d until week 12 (Figure 4.6a). Calves with GED, however, grew significantly slower than calves without GED in weeks 2 (-0.11 versus 0.24 kg/d) and 3 (0.38 versus 0.68 kg/d). LW and stature increased steadily in both groups, although calves with GED lost LW in week 2 and were consistently lighter and smaller in hip height and width from week 1 (Figure 4.6bcd).

Table 4.2: Mean (standard error) daily live-weight gain from birth to, and live weight, hip height and hip width at, four weeks of life, weaning (ten weeks of life) and twelve weeks of life, in heifer calves with (+) and without (0) gastrointestinal enteric disorder (GED)

	0 GED	+ GED	P
	Mean	Mean	
No, calves	30	23	
Daily live-weight gain from birth to			
4 weeks, kg/d	0.46 (0.026)	0.32 (0.029)	0.001
Weaning, kg/d	0.82 (0.016)	0.73 (0.019)	<0.001
12 weeks, kg/d	0.80 (0.016)	0.72 (0.018)	0.002
Live weight at			
Birth, kg	44.5 (0.91)	41.7 (1.04)	NS
4 weeks, kg	57.3 (1.12)	50.8 (1.38)	<0.001
Weaning, kg	102.1 (1.48)	92.5 (1.69)	<0.001
12 weeks, kg	108.7 (1.57)	99.7 (1.79)	<0.001
Hip height at			
4 weeks, cm	86.3 (0.47)	84.0 (0.54)	0.002
Weaning, cm	98.6 (0.56)	96.6 (0.64)	0.023
12 weeks, cm	101.2 (0.53)	99.2 (0.61)	0.015
Hip width at			
4 weeks, cm	19.0 (0.20)	18.4 (0.23)	NS
Weaning, cm	23.6 (0.19)	22.9 (0.22)	0.009
12 weeks, cm	25.2 (0.20)	24.9 (0.21)	0.020

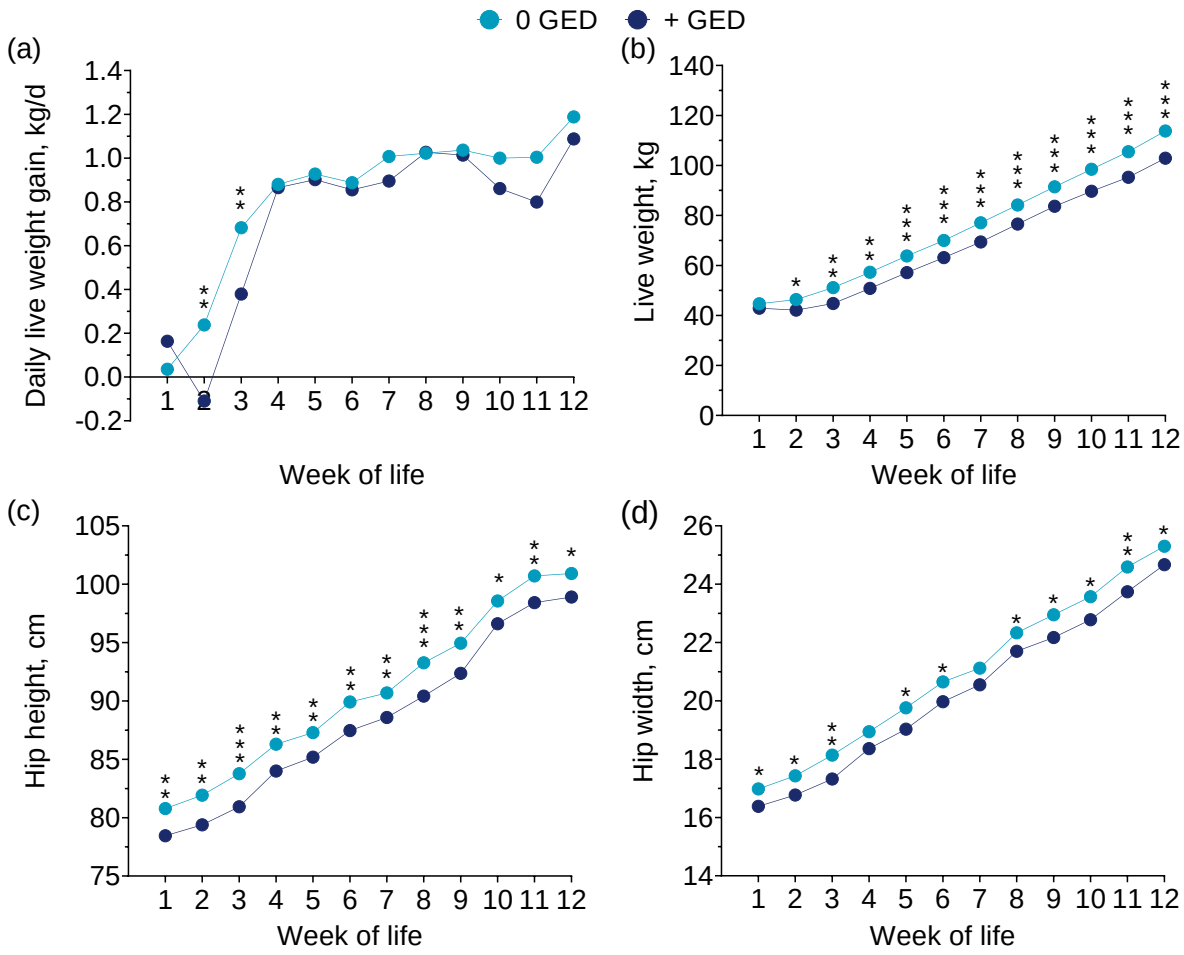


Figure 4.6: Mean daily live-weight gain (a), live weight (b), hip height (c) and hip width (d) of heifer calves with (+) and without (0) gastrointestinal enteric disorder (GED)in the first twelve weeks of life. Statistical significance is reported as ∗ for p<0.05, ∗∗ for p<0.01 and ∗∗∗ for p<0.001

Gompertz curves were a significant fit to LW data (p<0.001; Figure 4.7). Separate scaling factor (A) for each group was significant (p<0.001) indicating GED reduced average LW. Separate linear factor (C) for each group was significant (p<0.001) indicating GED reduced starting LW. Separate non-linear factors (B & M) for each group were not significant (p=0.399).

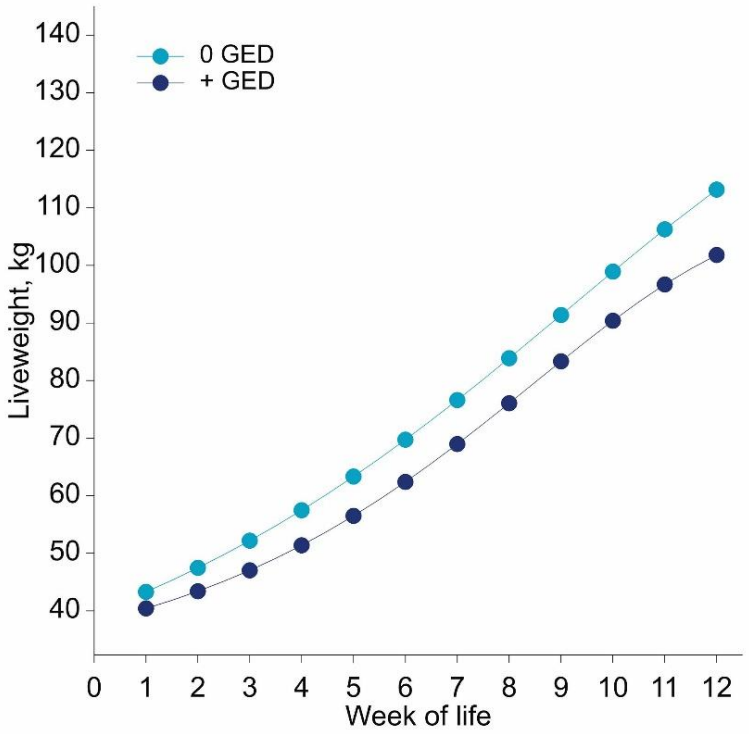


Figure 4.7: Best-fit curve for weekly live weight in heifer calves with (+) and without (0) gastrointestinal enteric disorder (GED) in the first twelve weeks of life by Gompertz model

4.3.3 Feed intake and efficiency

Calves with GED drank significantly less MR in the first four weeks of life than calves without GED (Table 4.3). MR intake was affected by age and GED (p<0.001). Linear and quadratic components in the model were significant for both age (p<0.001) and age*GED interactions (p=0.011) indicating MR intake curves were different for each group. Calves with GED consumed consistently less MR up to 53 days of age when peak MR allowance was reached (7.57 versus 7.02 L/d), and then consumed similar amounts during the step-down period. Weeks 2 and 3 were most significant for reduced milk intake when GED

calves drank respectively, 0.72 and 0.92 L less per day than calves with no GED (Figure 4.8a). GED calves were not able to compensate for their lower daily consumption in weeks 2 and 3, and their accumulated MR consumption was significantly lower from then onwards (Figure 4.9a).

There was no difference in daily or accumulated water intakes between groups (Table 4.3). Water intake increased steadily from week 1 to a mean of 1.74 L/d at week 9, and then increased rapidly at weaning to a mean of 15.0 L/d in week 12 (Figure 4.8b).

Table 4.3: Mean (standard error) total consumption of milk replacer, water, concentrate and straw at four weeks and twelve weeks of life in heifer calves with (+) and without (0) gastrointestinal enteric disorder (GED)

	0 GED	+ GED	P
	Mean	Mean	
4 week total			
Milk replacer, L	204 (5.3)	176 (5.5)	0.007
Water, L	16.6 (0.66)	16.4 (0.68)	NS
Concentrate, kg	0.47 (0.113)	0.50 (0.116)	NS
Straw, kg	0.20 (0.048)	0.08 (0.049)	NS
12 week total			
Milk replacer, L	473 (9.0)	433 (10.3)	0.006
Water, L	295 (4.5)	292 (5.2)	NS
Concentrate, kg	70.6 (2.68)	74.8 (3.07)	NS
Straw, kg	6.8 (0.57)	6.1 (0.58)	NS
Feed conversion ratio, kg DMI/kg LWG	2.0 (0.06)	2.2 (0.06)	0.025

Abbreviations: DMI, dry matter intake; LWG, live-weight gain

Calves began consuming straw and concentrate between weeks 3 and 4 (Figure 4.8bc). By week 6 GED calves were consuming more concentrate than calves without GED, although intake was not significantly different between groups (Table 4.3). Calves with GED ate on average 0.07 kg/d more straw than calves without GED between weeks 5 and 9, and then intake plateaued at 0.17 kg/d (Figure 4.8c) until week 12. Calves without GED ate significantly more straw than calves with GED after weaning, although, accumulated straw intake was not significantly different between groups (Table 4.3). GED calves had higher FCR than calves without GED.

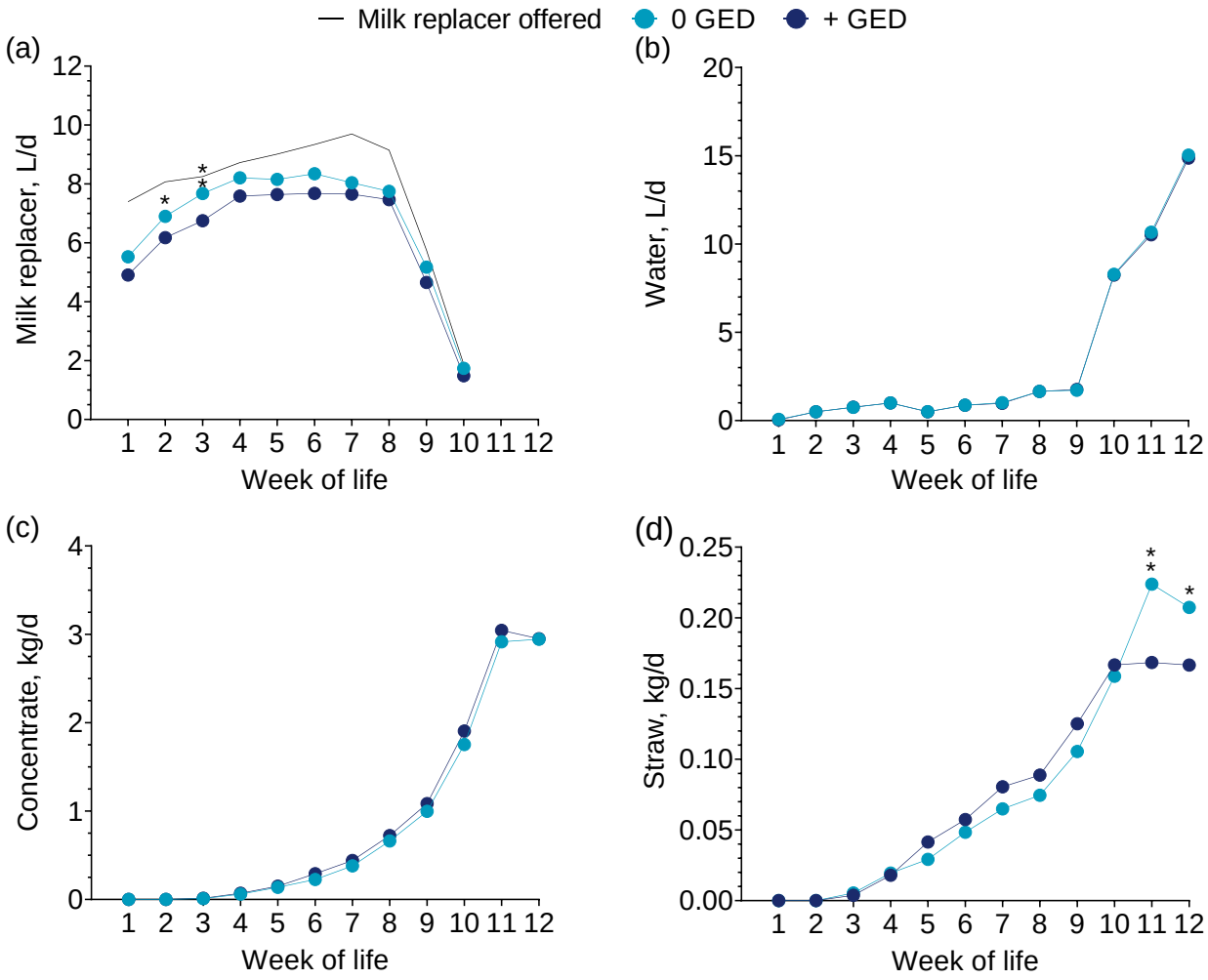


Figure 4.8: Daily consumption of (a) milk replacer, (b) water, (c) concentrate and (d) straw in the first twelve weeks of life in heifer calves with (+) and without (0) gastrointestinal enteric disorder (GED). Statistical significance is reported as ∗ for p<0.05, ∗∗ for p<0.01 and ∗∗∗ for p<0.001

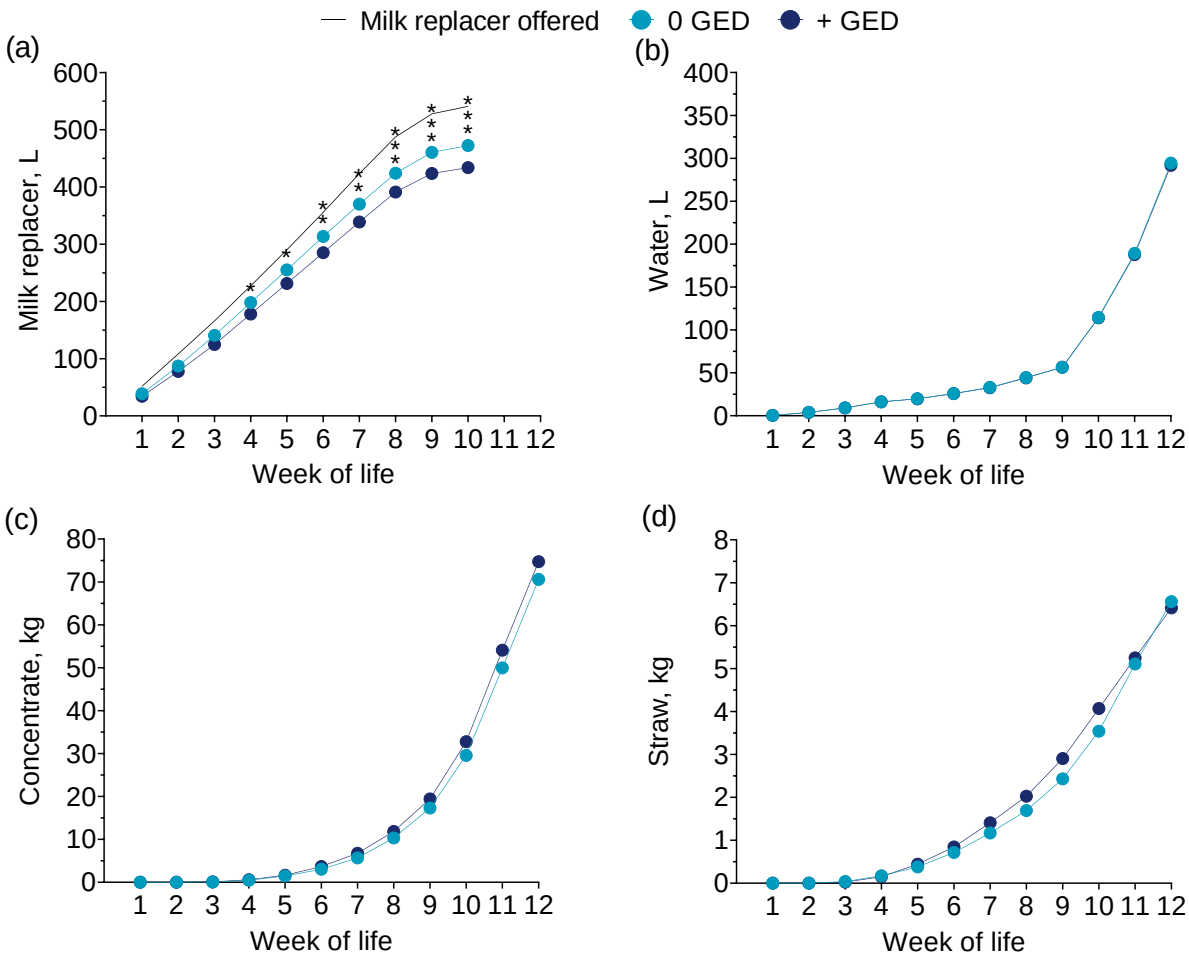


Figure 4.9: Accumulated consumption of (a) milk replacer, (b) water (c) concentrate and (d) straw in the first twelve weeks of life in heifer calves with (+) and without (0) gastrointestinal enteric disorder (GED). Statistical significance is reported as ∗ for p<0.05, ∗∗ for p<0.01 and ∗∗∗ for p<0.001

4.3.4 Milk feeding behaviour

Milk feeding behaviour data were similar throughout the study. However, calves with GED had significantly fewer unrewarded and total visits in week 2 (Figure 4.10bd), significantly more rewarded visits in week 3 (Figure 4.10c), and significantly fewer unrewarded visits as a proportion of total visits in week 2 and 3 (Figure 4.10f), than calves without GED. Calves without GED drank consistently faster each week, whereas drinking speed was delayed until week 3 in GED calves and then increased at a faster rate so that by week 10, calves with GED drank significantly quicker than calves without GED (Figure 4.10e). There was no difference between groups in number of breakoffs (Figure 4.10a).

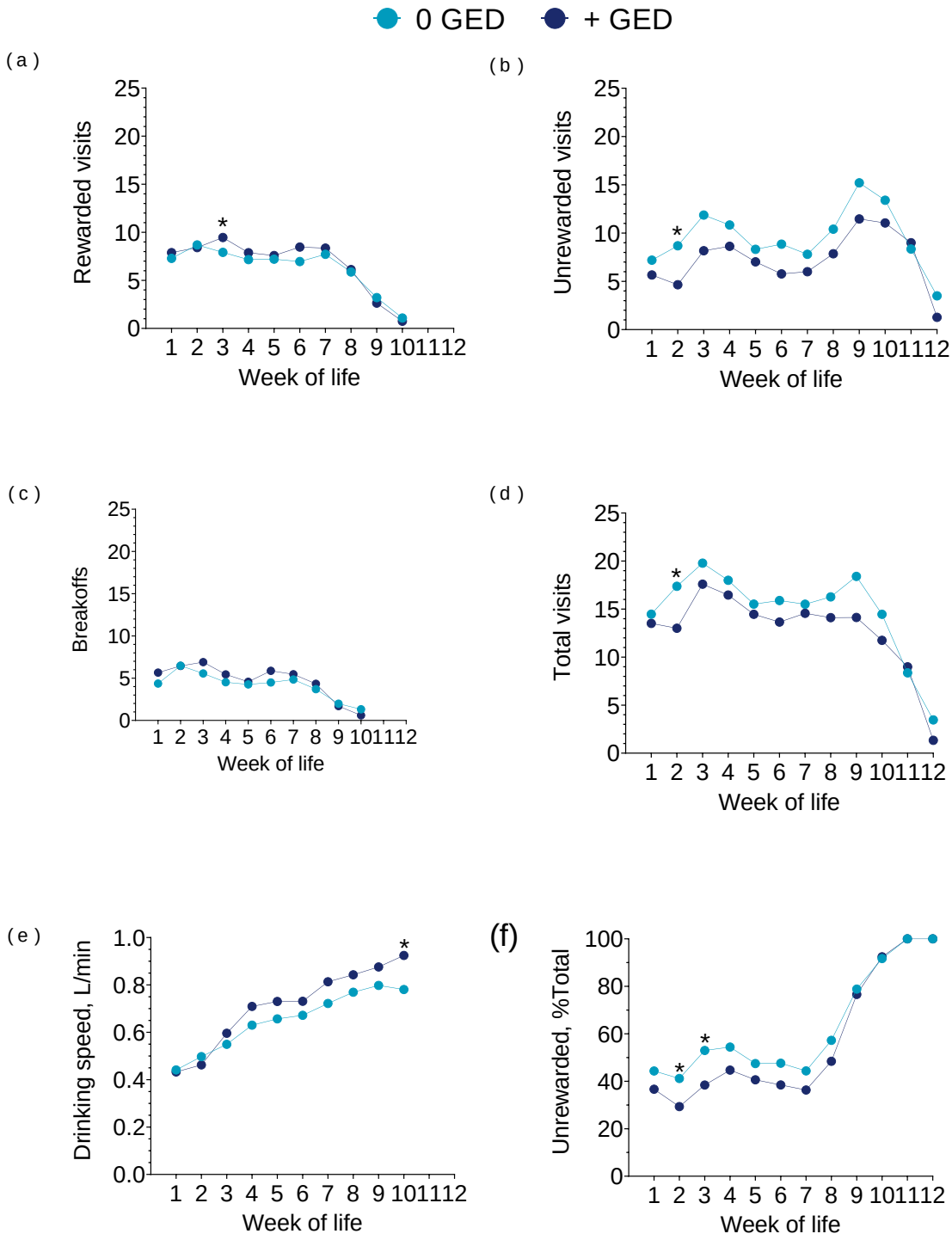


Figure 4.10: Milk feeding behaviours: (a) rewarded visits, (b) unrewarded visits, (c) breakoffs, (d) total visits, (e) drinking speed and (f) unrewarded visits as a proportion of total visits in heifer calves with (+) and without (0) gastrointestinal enteric disorders (GED) in the first twelve weeks of life. Breakoffs defined as when the calf stopped drinking before full milk allocation was consumed (Jorgensen *et al.*, 2017). Statistical significance is reported as ∗ for p<0.05, ∗∗ for p<0.01 and ∗∗∗ for p<0.001

4.4 Discussion

This study evaluated growth and behaviour from birth to 12 weeks of age of calves with and without GED. Specifically, the effect of GED in terms of feed intake and milk feeding behaviour and on weaning targets, which are not well documented.

4.4.1 Disease prevalence and treatment

In this study, GED was the most prevalent disease, affecting 43% of calves in the first 12 weeks of life. Although little is known of GED incidence in the UK, Johnson *et al.* (2011) concluded it is reasonable to expect a mean prevalence in dairy youngstock between 19 and 35% and for disease to be highly clustered. This is a smaller range than recent UK studies, which found average incidences of 7.7% (Hume *et al.*, 2018), 18.9% (Renaud *et al.*, 2020) and 48.2%(Johnson *et al.*, 2021). Calves were under close observation and were individually checked daily for ill health and abnormal faecal consistency. This may appear to inflate estimates compared to similar studies, however this may be because other less rigorous studies underestimated GED. Disease incidence in the current study could be inflated because Hume *et al.* (2018) determined disease incidence on 21 dairy farms in Kent using a questionnaire and farm records, Renaud *et al.* (2020) only took FCS at 0, 7, 14 and 28 days of age and Johnson *et al.* (2021) assessed calves weekly. However, 53 calves in the current study is a small cohort, and this should be considered when making comparisons between studies.

Calves with GED had a mean cumulated FCS score of 5 and scoured for 2 days on average. Other studies found calves scoured on average between 2 (Jenny *et al.*, 1978; Quigley *et al.*, 2006) and 7 days (Wickramasinghe *et al.*, 2019), but, although a higher observational FCS may be an indicator of increased GED severity (Renaud *et al.*, 2020), no other study has used cumulated FCS as a measure of disease burden. Because only 5 of 23 calves with GED had a cumulated FCS greater than 5 and scoured for more than 2 days, this could indicate most incidences were mild and therefore GED in this study could be described as low severity but highly prevalent. However, the ORS used in this

study addressed dehydration in calves with scour by offering an isotonic solution in water. Mixing ORS in milk is discouraged as this creates a hypertonic solution which can aggravate scour (Kameda *et al.*, 1968; Wilms *et al.*, 2019). Additionally, ORS may change palatability of milk and deter a calf from drinking (Mueller, 2018), risking the calf not consuming enough energy to achieve target DLWG. By offering an isotonic, highly palatable ORS solution a calf might have recovered quicker from a GED incident. Furthermore, as all calves were individually observed twice daily, checks were likely to have been more thorough than in commercial systems. This likely resulted in more timely intervention that prevented their condition from worsening.

Calves were on average 14 days old when diagnosed with GED, with 50% of incidents occurring between 10 to 15 days. Age distribution of disease was like Urie *et al.* (2018) and FCS was like Renaud *et al.* (2020). The main reason for high incidence at 14 days is thought to be due to a calf's weaker immune system as it transfers from passive to active immunity. The dip in antibodies increases a calf's susceptibility to disease and the calf is therefore at greatest risk of GED during the second week of life.

Respiratory symptoms were seen in 36% of calves, which was higher than expected as the new calf-rearing unit was constructed with low-height walls and high-pitched roof designed for optimum natural ventilation and draft reduction. Environmental sensors inside the unit measured mean temperature of 8.6˚C and humidity of 77.8% over the study (compared to 6.9˚C and 81.4% outside). Mean temperature was below the calf's thermo-neutral zone (<3 weeks old; 15 to 25 ˚C (Davis and Drackley, 1998; Stull and Reynolds, 2008), > 3 weeks old; 10 to 20 ˚C (Cattell, 2000; Silva and Bittar, 2019)) and increasing the amount of time a calf spends below its thermo-neutral zone, reduces DLWG (Bell *et al.*, 2021). Measures to reduce cold stress, such as feeding high levels of energy, using jackets and straw bedding to encourage nesting, were used in this study, but their effects were not quantified. BRD between 30 and 183 days (1 and 6 months) of age has been associated with previous scour (Hultgren *et al.*, 2008), however similar numbers of calves with (n=11) and without (n=8) GED were treated for respiratory symptoms. Additionally, calves were on average 54 days

of age when treated for BRD which coincided with the start of weaning at 53 days.

4.4.2 Live weight, daily gain, and stature

Calves with GED grew slower in the first four weeks of life, a period when feed conversion efficiency is high but calves are vulnerable to disease (Bach and Ahedo, 2008). DLWG in weeks 2 and 3 were most affected by GED and calves lost LW in week 2 when GED was most prevalent. This caused a delay in DLWG which was not regained later, so GED calves failed to achieve pre-weaning DLWG target (above 0.80 kg/d) and were consistently lighter and smaller in stature throughout the study than calves without GED. This negative impact on growth is consistent with other studies (Virtala *et al.*, 1996c; Windeyer *et al.*, 2014). Birth weight was lower in GED calves, although not significant, which supports associations between birth weight and subsequent disease and mortality (Linden *et al.*, 2009; Glover *et al.*, 2019). Calves without GED gained 3.7 kg more by week 4 and were 10% heavier than calves with GED. This LW advantage was maintained throughout the study. GED calves weighed 92.5 kg at weaning which, although meeting their LW target (minimum double birthweight ~ 90 kg), was still 10% lighter than calves with no GED. DLWG in GED calves dipped between weeks 9 and 12, which was not significant, but might be associated with greater weaning stress.

4.4.3 Feed intake and efficiency

Calves with GED drank less MR during weeks 2 and 3 which coincides with peak incidence of GED. This is not surprising as sick calves have supressed behaviour and reduced intake (Borderas *et al.*, 2009b; Lowe *et al.*, 2019). GED calves were not able to compensate after week 3 and MR intake plateaued around 7.6 L/d between weeks 4 and 8, after which MR allowance was reduced. This resulted in lower accumulated MR intake which was significantly less than for calves without GED. Consequently, GED calves grew slower and weighed less at weaning.

Six calves had a FCS of 1 at weaning. These calves perhaps had not fully transitioned from milk to solid feed, and their GIT was not adjusted to utilising higher levels of concentrates for energy. A lower nutrient intake around weaning results in acute short-term hunger and a rapid increase in starter intake, which creates rumen acidosis and acute disturbance of the GIT microbiome (Khan *et al.*, 2016; Gelsinger *et al.*, 2020).

Both groups consumed concentrate and straw from week 3 and daily intake increased exponentially until week 10 where straw intake then plateaued. However, calves with GED plateaued at a significantly higher intake than calves without GED at week 11 and 12. This significance may be associated with their MR intake which plateaued at this time and rumen development. The concentrate was manufactured to be textured and palatable. Palatability is important to encourage early voluntary intakes (Moriel and Arthington, 2013; Caramalac *et al.*, 2017) and dietary fibre (either through forage or a coarse concentrate) has been found to prevent hyperkeratosis in the rumen by physically abrading the rumen epithelium (Drackley, 2008). A coarse concentrate has also been shown to have higher intakes and DLWG (Ghaffari and Kertz, 2021) however, ingredients must be of equal size and palatability to prevent sorting. Finer ground particles undergo starch fermentation more rapidly causing digestive disorders (Bach *et al.*, 2007; Bateman *et al.*, 2009). This is a possible explanation for calves with abnormal faecal scores after 21 days of age.

Mean concentrate intake at 10 weeks for calves with and without GED was 1.91 and 1.75 kg/d respectively which met the 1.5 to 2.0 kg/d targets for weaning calves according to their daily concentrate intake. This target is given because metabolisable energy (ME) in MR is typically twice the ME in concentrate therefore, for every litre MR is reduced (containing 130 to 150 g MR), a calf needs to consume 250 g of concentrate. Ideally, calves should be weaned when they are consuming this concentrate target for three consecutive days.

An unexpected observation was the plateau in straw intake after weaning in calves. Inclusion of forage in the diet is debated. Forage inclusion has been shown to reduce concentrate intake due to increased gut fill from accumulated

undigested fibrous material in the reticulorumen, which causes calves to become pot-bellied (Drackley, 2008). However, other studies found forage inclusion encouraged concentrate intake (Castells *et al.*, 2012; Terré *et al.*, 2015) and rumen development (Beiranvand *et al.*, 2014; Nemati *et al.*, 2015), and can reduce acidosis and hyperkeratosis (Heinrichs, 2003; Kim *et al.*, 2016). Feeding average quality chopped forage, as in this study, rather than high quality forage, is recommended to avoid high forage intake, and smaller particle size has been found to reduce the effect on gut fill (Castells *et al.*, 2013; Aragona *et al.*, 2020). Other studies, however, have found no effect of forage particle size or inclusion level on concentrate intake (Bagheri *et al.*, 2021). It could be speculated that calves with GED experienced subacute rumen acidosis after week 8, due to reduced MR and continued high intakes of concentrate, and this encouraged a higher voluntary straw intake to rebalance rumen pH.

Water intake did not differ between groups of calves, although only weekly pen measurements were taken, which is a limitation to this work. GED calves might be expected to drink more water due to depressed appetite before disease onset (Lowe *et al.*, 2019). Borderas *et al.* (2009a) (Borderas *et al.*, 2009a) found milk consumption to be significantly influenced in sick calves fed high milk allowances (12 L/d) compared to those fed low milk allowances (4 L/d). However, this difference was most apparent between days dehydration (Jenny *et al.*, 1978; Wenge *et al.*, 2014), although this may be counteracted by lethargic behaviour. Lowe *et al.* (2019) found there was no change in number of water trough visits, but visit duration increased pre-disease presentation. Because water intake was based on pen measurements, any changes in calves with GED may be negated by their pen mate without GED. Season of year may have influenced water intake, but this effect has been found minor (Kertz *et al.*, 1984).

4.4.4 Milk feeding behaviour

Calves with GED drank less MR and had fewer unrewarded visits to the ACF in the first four weeks of life, which supports previously recorded behaviours associated with ill health. Drinking speed was expected to be different too as Maatje *et al.* (1993) reported that reduced drinking speed was a reliable

indicator of disease, however, no difference was observed in the current study except during the last week of milk feeding when calves with GED drank much faster than those without GED.

Milk intake has been found the only feeding behaviour to show a significant change pre-disease diagnosis with greater differences in intake most apparent between days 0 and 3 of disease diagnosis and at greater feeding levels (MR offered= 12 L/d; Borderas *et al.,* 2009b). The effect of feeding level is thought to be because increased feeding motivation, caused by a low milk allowance, reduces the effect of disease on feeding behaviour. Although calves in the current study were provided with up to 10 L/d, changes in milk feeding behaviour may have been greater if calves were provided with a higher milk allowance. Nevertheless, even calves without GED did not drink their full MR allowance.

Breakoffs were thought to reflect suck reflex and remained proportional to rewarded visits in both groups. GED calves were expected to have more breakoffs due to a weaker suck reflex associated with sick calves, however no significant difference was observed. Calves were manually pushed up to the ACF by farm staff if they had more than 3 L left of their allowance to drink. GED is known to be painful (Todd *et al.*, 2010), therefore calves which showed lack of vigour, hunger, and activity, and were most likely sick, were also those with greater MR allowance remaining and were pushed up. This may explain why GED calves had unexpectedly higher rewarded visits in week 3, which coincides with when GED was most prevalent. Healthy calves were more likely to drink their entire allowance uninterrupted, so therefore had fewer rewarded visits.

Svensson and Jensen (2007) suggested that unrewarded visits were a useful indicator of disease and was the most sensitive behaviour compared with drinking speed, MR intake and feeding duration. Unrewarded visits represent calves entering the ACF to see whether milk is available, therefore a decrease in unrewarded visits suggests reduced appetite. This suggestion is supported by the current study, where calves with GED had significantly fewer unrewarded

visits during week 2 when GED was most prevalent, and calves drank significantly less MR.

4.4.5 Limitations

Concentrate, straw, and water intakes were measured on a pen basis. Although MRI was recorded individually, pen mates can restrict access to feeders and affect an individual's MRI, which in turn could affect growth rate. Calculating individual intake from pen measurements is a limitation to this work, however housing calves in pairs was a requirement of Home Office and the farm's Tesco contract.

4.5 Conclusion

In this study, GED could be described as a highly prevalent, low severity disease affecting four in ten calves in the pre-weaning period. GED significantly reduced DLWG and MR intake of calves in their first four weeks of life, which is a period when feed efficiency and disease vulnerability are highest. This is important when considering rearing costs, performance, and efficiency. This impact could not be compensated later in the pre-weaning period and decreased weaning LW by 10%, an important timepoint in heifer rearing which influences future performance. Strategies to reach high milk feeding levels during the first four weeks of life, and thus achieve DLWG targets sooner, are critical to alleviating this impact. No difference in water, straw and concentrate intake was observed, except after weaning when calves with GED had a higher plateau in straw intake. Lower MR intake and more unrewarded visits were associated with calves with GED, therefore demonstrating potential as early indicators of disease. Integration of these measures into an automated system could enable earlier intervention including use of preventative ORS. In addition to facilitating on-farm decision-making, development of such tools would reduce treatment costs and increase heifer rearing efficiency and performance, ultimately improving calf health and welfare.

Chapter 5

The cost of bovine respiratory disease

5.1 Introduction

Bovine respiratory disease (BRD) is a global impediment to rearing replacement heifers in terms of welfare and financial cost. It is a complex disease that describes a range of upper respiratory infections and several varieties of pneumonia (Gaudino *et al.*, 2022), which are caused by several risk factors including nutritional, environmental and management changes, particularly in the pre-weaning period of a heifer (Taylor *et al.*, 2010). In younger animals, the main bacterial sources are *Mannheimia haemolytica*, *Pasteurella multocida*, *Histophilus somni* and *Mycoplasma bovis* (Lima *et al.*, 2016), which can colonise the weakened lung following environmental stressors and viral infection. As a result, clinical signs are often observed at or following weaning when heifers are first mixed with groups of older animals (McGuirk, 2008). To reduce incidence of BRD, common practices include good colostrum management, vaccination, and correct ventilation (Gorden and Plummer, 2010).

BRD affects almost 1.9 million cattle in the UK each year (Nicholas, 2011). BRD is the leading cause of mortality in early calfhood (46.5%; USDA, 2010) with up to a 52% incidence risk during the pre-weaning period (Guterbock, 2014; Atkinson, 2015). It is an expensive disease and difficult to value; losses to the cattle industry are estimated between £50 million and £80 million annually, with cases ranging from £30 for mild outbreaks to £500 in the event of death (ADAS, 2013; Statham, 2013). The economic viability of dairy systems can be significantly impacted by not only the direct costs of calf morbidity and treatment but also hidden costs of reduced performance. Studies have found that incidence of BRD before first calving causes higher pre-calving mortality (Waltner-Toews *et al.*, 1986b); lower daily live-weight gain (DLWG) (Virtala *et al.*, 1996b; Donovan *et al.*, 1998b), delayed age at first calving (AFC) (Correa *et al.*, 1988; Warnick *et al.*, 1994; Bach, 2011); greater risk of dystocia (Warnick *et al.*, 1994) and halves the likelihood to survive first lactation when treated on four or more occasions (Bach, 2011). On the other hand, Warnick *et al.* (1994,1997) found calfhood BRD was not associated with first lactation milk yield or post-calving mortality. However, effects may have been underestimated

due to poor recording of disease in heifers, which makes it difficult for producers to associate calf hood disease with long-term negative outcomes.

The first aim of this study was to analyse the effect of BRD on age and live weight (LW) at first calving and rearing costs in heifers reared in a fully-housed system. The second aim was to determine the effect of BRD on subsequent performance and survivability which is currently largely unknown in the UK.

5.2 Materials and methods

5.2.1 Animals and location

This was a retrospective study using Holstein-Friesian heifers born at the Nottingham University Dairy Centre between 2014 and 2018. Veterinary treatments were recorded routinely from 2014 for both bull and heifer calves, but only heifer calves that had a recorded date of first calving were included in this study (n=467). Herd lifetime data were analysed from 267 culled adult cows, therefore cows which had not been culled (n=200) were excluded from productivity and longevity analyses. From 267 culled adult cows, there were 95 which did not calve for a second time and were excluded from analysis of first lactation milk yield.

5.2.2 Management

All heifers were fed, housed and treated as described in 2.2 Youngstock management and mated as described in 2.4 Heifer and cow reproduction.

5.2.3 Data collection

Data were extracted from the herd management database (Uniform-Agri Professional, UK) using Microsoft SQL Server Management Studio database software linked to the lactating cow software (Time4Cows; T4C, Lely Ltd., UK).

5.2.3.1 BRD treatment data

Data of disease-related treatment were extracted from animal health records and the Uniform database. Data were collated in Excel and categorised

according to age at treatment: 0 to 48 hours, 48 hrs to 30 days, 30 days to 6 months, 6 to 12 months, and 12 months to calving, along with season of treatment: spring (March to May), summer (June to August), autumn (September to November) and winter (December to February). Heifers were grouped according to number of BRD treatments received between birth and first calving; 0, 1, 2, 3 or ≥4 treatments.

5.2.3.2 Live weight and age-related data

LW was measured using load cells fitted to the automatic milking system (AMS; Lely Astronaut, Lely Ltd., UK) and extracted from T4C using SQL. LWFC was calculated as mean LW in the first 7 days post-partum. Herd mature weight (MW) for each year of birth was calculated from mean LW of cows in third lactation and above and between 100 and 200 days in milk (DIM) and used to calculate 55% and 85% MW. Days to 55% and 85% MW were calculated by dividing LW at 55 and 85% MW by estimated DLWG. Estimated DLWG from birth to first calving was calculated by subtracting 41 kg (assumed birth weight (Archer, 2021)) from LW at first calving (LWFC) and dividing by AFC.

5.2.3.3 Productivity and longevity data

Data for milk yield and DIM per lactation, and culling date, were extracted from T4C using SQL, and collated in Microsoft Office Excel (2016). Average daily yield in first lactation was calculated as first lactation yield divided by DIM for first lactation. Lifetime milk yield was calculated as sum of milk yield from each lactation. Lifetime DIM was calculated as sum of DIM for each lactation. Lifetime daily yield (LDY) was calculated as lifetime milk yield divided by culling age (days). Culling age was calculated by subtracting date of birth from date of culling. Additional gross margin was calculated using the difference between lifetime milk yield in heifers with no BRD and each treatment group, multiplied by gross margin per litre of milk in the Farm Business Survey (£0.15/L; 2020/2021 Farm Business Survey).

5.2.3.4 Cost of BRD

Rearing costs were calculated using an estimate from Boulton *et al.* (2017) of £2.87, This was adjusted for differences in LW and DLWG by multiplying £2.87 by % LW difference between mean LWFC of heifers with no BRD (LW^0) and each treatment group (LW^t). This number was then multiplied by the number of days over AFC target (730 days).

$$Rearing\ cost = \frac{LW^t}{LW^0} \times £2.87 \times No.d\ over\ 730\ d$$

Milk loss was defined as the loss of income from first lactation milk sales as a result of rearing non-lactating animals beyond 730 days. Milk loss was calculated from the average first lactation milk yield (12,273 L) of cows which had calved a second time (n=172). This was divided by average DIM (327 DIM) and multiplied by average price of milk between 2014 and 2018 (£0.28/L; National Statistics (2014-2018) and number of days over the AFC target.

$$Milk\ loss = \frac{12{,}273}{327} \times £0.28 \times\ No.d\ over\ 730\ d$$

Treatment costs were calculated by volume of drug used per treatment multiplied by frequency. Draxxin was used to model treatment costs as it was the most commonly used antibiotic against BRD between 2014 and 2018. For each treatment, an average of 2ml of Draxxin 100mg and 4 ml of Metacam 20mg was required, which was calculated as a proportion of the costs of 100ml of drug; where D_m was the cost of 100ml of Metacam (£41.67) (Farmacy, 2020a) and D_d was the cost of 100ml of Draxxin (£295.10) (Farmacy, 2020b).

$$Treatment\ cost = \left((0.04 \times D_m) + (0.02 \times D_d)\right) \times No.treatments$$

Labour costs were calculated by average employee cost (£18.62/hr; Nottingham, 2022) multiplied by estimated time per handling (0.25 hr) and the number of heifer handlings per treatment (n=2), and then multiplied by number of treatments.

$$Labour\ cost = 18.62 \times 0.25 \times 2\ \times\ No.treatments$$

Total cost was calculated by taking the sum of costs for feed, milk loss, treatment, and labour. Additional % of rearing cost was calculated by dividing total cost by £1819, which is the estimated rearing cost per heifer (Boulton *et al.*, 2017). Cost difference was the difference in total rearing cost between the 0 BRD group and each treatment group (1 to ≥ 4).

5.2.4 Statistical analysis

Data were collated using Microsoft Office Excel (2016) and analysed using GenStat (21st edition; VSN International, UK). Data for distribution of treatments according to age of treatment and season of birth were analysed using Generalized Linear Models (GLM) with season of birth as a fixed effect and Poisson error distribution with a log-linear function. Data for distribution of treatments according to age and season of treatment were analysed using chi-square contingency tables. Performance data categorised by season of birth and BRD treatment were analysed using residual maximum likelihood model with BRD treatment as fixed effect. Normal error distribution was used for LW and milk production data; Poisson error distribution with a log-linear link function was used for data related to days and number of treatments. For variables with a dispersion parameter below 1, dispersion parameter was fixed at 1, and for variables with a dispersion parameter above 1, dispersion parameter was estimated. Statistical significance was reported at $p<0.05$ and differences between treatments were compared using Bonferroni test with a 95% confidence interval. Tabulated means are presented with their standard error (SE) and statistical non-significance is reported as NS.

5.3 Results

5.3.1 Age and seasonal distribution

Of 467 heifers which survived to first calving between 2014 and 2018, 65% (n=303) received 812 treatments for BRD. Most treatments (n=564) were administered to 52.3% of heifers between 30 days and 6 months of age (Figure 5.1). Between 48 hrs and 30 days of age, 192 treatments were given to 28.7% of heifers. Relatively few heifers received BRD treatment between the ages of 0 and 48 hours (0.4%), 6 and 12 months (5.2%), or 12 months and calving (0.4%).

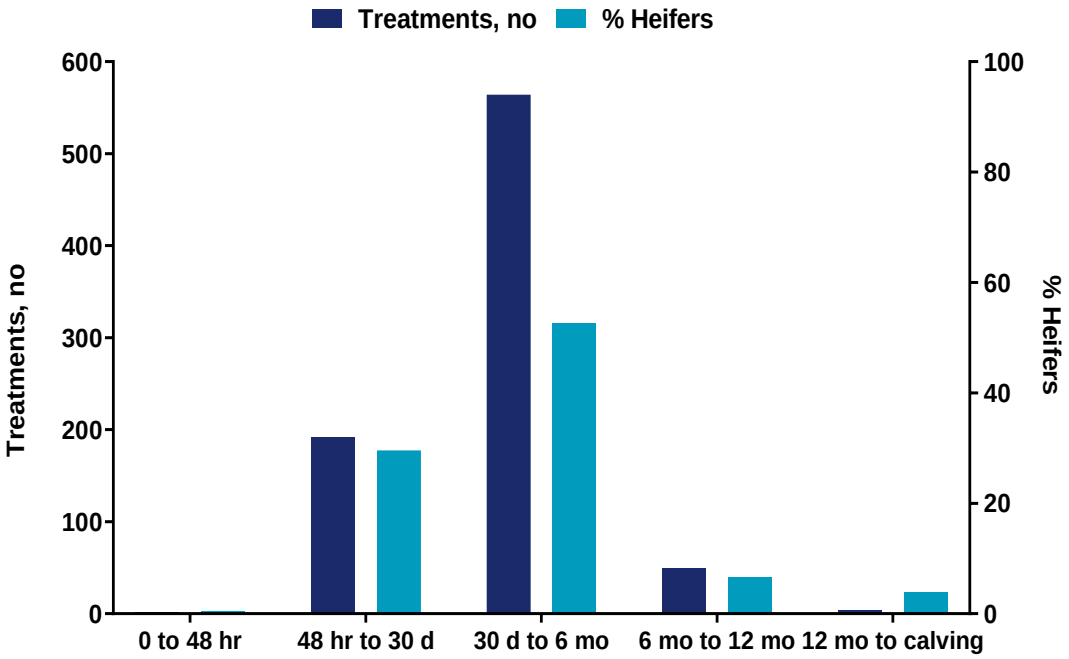


Figure 5.1: Age distribution of number of treatments administered (n=812) and proportion of heifers receiving treatment for bovine respiratory disease (n=303) between birth and first calving

Table 5.1: Age distribution of mean number of bovine respiratory disease treatments administered between birth and first calving per heifer, according to season of birth

	Season of birth				P
	Spring	**Summer**	**Autumn**	**Winter**	
Heifers, no	101	112	128	126	
Treatments per heifer:					
0 to 48 hr	0.0 (0.00)	0.0 (0.00)	0.0 (0.01)	0.0 (0.01)	NS
48 hr to 30 d	0.5 (0.07)	0.3 (0. 05)	0.4 (0.05)	0.4 (0.05)	NS
30 d to 6 mo	0.9 (0.10) [a]	1.7 (0.14) [b]	1.3 (0.10) [ab]	1.1 (0.09) [a]	0.002
6 mo to 12 mo	0.2 (0.05) [b]	0.1 (0.02) [ab]	0.0 (0.01) [a]	0.0 (0.02) [a]	<0.001
12 mo to calving	0.0 (0.00)	0.0 (0.00)	0.0 (0.01)	0.0 (0.01)	NS
Total	1.6 (0.13) [ab]	2.1 (0.15) [b]	1.7 (0.12) [ab]	1.5 (0.11) [a]	0.036

[abc] Statistical significance ($p<0.05$) is reported with different letters

Heifers born in summer received the greatest number of treatments between birth and first calving, followed by autumn, spring then winter (Table 5.1). Age distribution of treatments varied between seasons (Table 5.2) and there was a difference between seasonal means (Pearson chi-square value = 68.71 with 12 d.f., $p<0.001$). Of the total number of treatments administered, 37% were administered during winter, 29% during autumn, 21% during spring and 13% during summer (Table 5.2). Most treatments (n=197) were administered to heifers between 30 days and 6 months during the winter.

Table 5.2: Age distribution of bovine respiratory disease treatments by season of treatment in heifers between birth and first calving

	Season of treatment				Total
	Spring	**Summer**	**Autumn**	**Winter**	
Treatments, no	167	104	238	303	812
Age at treatment					
0 to 48 hrs	1	0	0	1	2
48 hrs to 30 d	55	34	41	62	192
30 d to 6 mo	110	64	193	197	564
6 mo to 12 mo	1	6	4	39	50
12 mo to calving	0	0	0	4	4

Heifers born in spring and summer calved later (up to 12 days) than heifers born in autumn and winter (Table 5.3). Heifers born in spring had an estimated DLWG of 0.79 kg/d which was greater than heifers born in summer, autumn and winter which grew at 0.77 kg/d. There was no difference between season of birth in LWFC.

Table 5.3: Mean (standard error) age and live weight at first calving and daily live-weight gain in heifers that survived to first calving (n=467) between 2014 and 2018, according to season of birth

	Season of birth				P
	Spring	**Summer**	**Autumn**	**Winter**	
Heifers, no	101	112	128	126	
First calving:					
Age, days	769 (6.8) [b]	773 (5.6) [b]	761 (5.6) [a]	762 (5.7) [a]	0.027
Live weight, kg	651 (5.2)	633 (5.1)	627 (5.1)	631 (5.2)	NS
Daily live-weight gain, kg/d	0.79 (0.008) [b]	0.77 (0.007) [a]	0.77 (0.007) [a]	0.77 (0.007) [a]	<0.001

[abc] Statistical significance (p<0.05) is reported with different letters

Table 5.4: Mean (standard error) age and live weight at first calving, daily live-weight gain, and age at 55% and 85% mature weight (MW) in heifers that survived to first calving between 2014 and 2018 (n=467), according to number of bovine respiratory disease treatments administered from birth to first calving

	Treatments administered, no					P
	0	**1**	**2**	**3**	**≥4**	
Heifers, no	164	105	74	53	71	
Age at:						
First service, days	447 (4.3) [a]	446 (6.9) [a]	458 (7.8) [ab]	463 (8.7) [ab]	482 (7.8) [b]	<0.001
First calving, days	747 (5.5) [a]	748 (8.8) [a]	764 (9.9) [ab]	769 (11.2) [ab]	788 (10.0) [b]	<0.001
Live weight, kg	634 (4.4)	637 (7.0)	635 (7.9)	638 (8.9)	627 (8.0)	NS
Daily live-weight gain, kg/d	0.791 (0.01) [b]	0.796 (0.01) [b]	0.777 (0.01) [ab]	0.774 (0.01) [ab]	0.744 (0.01) [a]	<0.001
Age at:						
55% Mature weight, days	485 (4.9) [a]	483 (7.8) [a]	497 (8.8) [ab]	499 (9.9) [ab]	520 (8.9) [b]	<0.001
85% Mature weight, days	721 (6.5) [a]	719 (10.4) [a]	738 (11.6) [ab]	740 (13.1) [ab]	767 (11.8) [b]	<0.001

[abc] Statistical significance (p<0.05) is reported with different letters

5.3.2 Rearing performance

On average, heifers born between 2014 and 2018 calved at 759 ± 72 days with 88.4 ± 7.8% maturity and had an estimated DLWG of 0.78 ± 0.08 kg/d. Heifers that received 4 or more treatments during the rearing period were 35 days and 41 days older at first service and at first calving, respectively, than heifers that received no treatment (abc Statistical significance ($p<0.05$) is reported with different letters

Table 5.4). Heifers that received ≥4 treatments for BRD had the highest AFS and AFC; heifers receiving no treatment had the lowest AFC. There was no difference in LWFC between treatment groups. Heifers receiving ≥4 treatments grew at 0.05 kg/d slower than heifers receiving no treatment. Heifers that received no treatment reached 55 and 85% MW 35 and 46 days earlier than heifers receiving ≥4 treatments.

5.3.3 First lactation and lifetime performance

There was no effect of BRD on first lactation yield, with heifers on average producing 12,273 ± 3,041 L. However, results for lifetime performance and longevity suggest that heifers with no BRD performed less well than other groups. Compared to heifers receiving no treatment, heifers receiving ≥4 treatments produced 14,910 L more milk over their lifetime and 5.3 L more milk per day of life, had 347 more DIM, were 444 days older at culling, and survived 0.9 additional lactations (.

Table 5.5). Heifers treated ≥4 times produced the highest additional gross income from milk sales.

Table 5.5: Mean (standard error) performance and longevity data for heifers that calved a second time (n=267), according to number of bovine respiratory disease treatments received between birth and first calving

	Treatments administered, no					P
	0	**1**	**2**	**3**	**≥4**	
Heifers, no	96	55	33	32	51	
Performance						
First lactation yield, L	11,901 (439)	12,665 (494)	12,329 (649)	12,899 (547)	11,739 (530)	NS
Lifetime milk yield, L	18,175 (1699) [a]	26,871 (2292) [b]	26,002 (3033) [ab]	31,089 (2900) [b]	33,085 (2647) [b]	<0.001
Lifetime daily yield, L/d	11.9 (0.69) [a]	16.1 (0.93) [b]	15.7 (1.23) [ab]	18.6 (1.17) [b]	17.2 (1.07) [b]	<0.001
Lifetime days in milk	464 (34) [a]	657 (55) [b]	643 (72) [ab]	746 (74) [b]	811 (70) [b]	<0.001
Additional gross margin	£ -	£1,315.35	£1,183.91	£1,953.37	£2,255.28	
Longevity						
Culling age, days	1283 (43) [a]	1496 (62) [ab]	1516 (83) [ab]	1608 (82) [b]	1727 (77) [b]	<0.001
Lactation of culling	1.8 (0.13) [a]	2.3 (0.20) [ab]	2.2 (0.26) [ab]	2.5 (0.27) [b]	2.7 (0.25) [b]	0.008

[abc] Statistical significance (p<0.05) is reported with different letters

5.3.4 Rearing costs

Heifers that received ≥4 treatments were estimated to cost £651.13 more per heifer, in rearing costs, milk losses, treatment and labour, then heifers that received no treatment (Table 5.6). Additional costs for heifers receiving no treatment were estimated to be £229.28 due to extra rearing costs and losses in milk yield potential for calving beyond the target 730 days. Treatment and labour together cost £67.52 per heifer treated ≥4 times, but the biggest cost was milk loss (£648.27), followed by extra rearing costs (£164.62). This gave a total of £880.41 which was estimated to be an additional 48.4% of the average rearing cost per heifer.

Table 5.6: Rearing costs by number of bovine respiratory disease treatments administered to heifers between 2014 and 2018

	Treatments administered, no				
	0	**1**	**2**	**3**	**≥4**
Heifers, no	164	105	74	53	71
Cost per heifer					
Rearing	£39.27	£41.78	£78.66	£90.66	£164.62
Milk loss	£190.01	£201.19	£380.02	£435.91	£648.27
Treatment	£0.00	£7.57	£15.14	£22.71	£30.28
Labour	£0.00	£9.31	£18.62	£27.93	£37.24
Total cost per heifer	£229.28	£259.84	£492.44	£577.20	£880.41
% Of rearing costs	12.6%	14.3%	27.1%	31.7%	48.4%
Total cost difference	£0.00	£30.56	£263.16	£347.92	£651.13

5.4 Discussion

This study evaluated the performance and costs associated with heifers treated for BRD. Specifically, the effects of BRD in terms of rearing targets and costs, and on lifetime performance which, to date, is not well documented.

5.4.1 Growth rate

For dairy heifers to calve at 730 days (24 months) with correct maturity, a DLWG of 0.75 to 0.80 kg/d is recommended between birth and first calving

(Cooke and Wathes, 2014). The current study found that heifers receiving ≥4 treatments for BRD in the rearing period grew, on average, 0.05 kg less a day, and did not meet DLWG targets. These heifers had the lowest estimated DLWG of 0.74 kg/d. This is consistent with Virtala *et al.* (1996), who found that commercial dairy calves receiving treatment for BRD had the lowest DLWG, 0.66 kg/d, at 30 days of age compared to their healthy herd mates. Similarly, Donovan *et al.* (1998) reported that increased BRD treatment before 183 days (6 months) of age significantly lowered DLWG, by 0.02 kg/d, in the subsequent pre-pubertal period between 183 and 426 days (6 and 14 months) of age.

These studies looked at growth in the early stages of the rearing period which may be important when discussing the role of LW at disease onset and effects of BRD. Targets of 0.80 to 0.90 kg/d have been suggested between 0 and 91 days (0 and 3 months) to optimise feed efficiency and growth in the early stages of development (Margerison and Downey, 2005). However, feeding for a higher level of growth and LW may also have protective effects against disease during pre-weaning, when risk of BRD is highest. Stanton *et al.* (2012) suggested that disparity in heifer size may influence an animal's response to BRD. The current study was limited to estimating growth from birth to calving and was unable to examine direct associations between early growth, LW and BRD. Therefore, future studies should investigate the practicalities of achieving growth rates between 0.80 and 0.90 kg/d during this period and effects of BRD in heifers fed an elevated plane of nutrition pre-weaning.

DLWG has been found to vary within groups of heifers from the same farm, with differences in early life environmental conditions and calf health contributing significantly to this variation (Brickell *et al.*, 2009a). Gastrointestinal enteric disorder (GED) is typically observed in the first month of life and is known to considerably reduce early DLWG, as well as to weaken resistance to subsequent disease. GED was not recorded during this study period, therefore the effect of previous health status on BRD cannot be determined, and this should be considered for future studies.

Guterbock (2014) indicated that severity and duration of infection may have a greater impact than incidence alone, suggesting that chronicity increases

adverse effects on LW. This also supports Donovan *et al*. (1998) who measured severity according to days treated. They found that a heifer treated for, on average, 6 days before 183 days (6 months) of age, would take an additional 4 days to reach the same mating LW as her healthy herd mates. However, many poor-growing heifers in their study were culled between weaning and mating which would underestimate the influence of disease on achieving LW at mating. Although severity of disease could not be measured in the current study, a similar delay in reaching target LW was observed, as heifers treated ≥4 times took 35 days longer to reach recommended mating LW of 55% MW.

5.4.2 Age and live weight at first calving

Lower DLWG did not reduce LWFC in heifers that were treated for BRD repeatedly (≥4) as these heifers calved at a later age and therefore had an additional 41 days to grow compared to their healthy herd mates. Margerison and Downey (2005) suggest a target of 85 to 90% MW is optimum at first calving. Between 2014 and 2018, the MW in this herd averaged 718 kg, which equates to a LWFC target between 610 and 646 kg. All heifers met this target, calving on average at 634 kg and 88.4% MW.

Studies have shown that heifers which calve between 700 and 760 days (23 to 25 months) are most economical, due to lower rearing costs and greater herd productivity (Cooke *et al.*, 2013; Wathes *et al.*, 2014; Boulton *et al.*, 2017). In the current study, AFC increased with number of BRD treatments, with only heifers receiving 0 or 1 treatment calving within target range for AFC, and heifers receiving ≥4 BRD treatments calved last at 788 days. This negative association with a later AFC is consistent with other studies, although length of delay varies. Warnick *et al.* (1994) found the delay in AFC to be almost double that of the current study, with heifers calving 90 days later when treated in the first 91 days (3 months) of life. However, Bach *et al.* (2011) found heifers with ≥4 BRD cases calved only 8 days later than those with no BRD, but these heifers were calving at a younger age than in the current study.

5.4.3 Seasonal effects

The current study found that 37% of BRD treatments were administered during winter, suggesting that calves born during autumn and winter are more likely to be treated for BRD than calves born in spring and summer. This is consistent with reports that BRD incidence is higher in autumn and early winter months due to differences in environmental temperature and humidity (Cusack *et al.*, 2003; Taylor *et al.*, 2010). Buczinski *et al.* (2017) (Buczinski *et al.*, 2017)found lung lesions in pre-weaned calves were almost twice as prevalent during winter than in summer (15% versus 8%). This discrepancy could be an effect of cold stress (4.7°C and 68.2% humidity), which has been shown to increase respiratory disease and antibiotic treatment compared with calves not experiencing cold stress (15.5°C and 59% humidity; Gorden and Plummer, 2010). Because colder temperatures and drafts are experienced during the winter period, studies suggest that housing and ventilation affect BRD incidence. The goal in winter is to minimize airborne pathogen density, remove excess moisture, and maintain adequate ambient temperature (10ºC to 13ºC) through efficient ventilation. A compromise between removal of airborne contaminants and maintenance of ambient temperature is important in winter ventilation.

Exposure to airborne pathogens can be increased by overcrowding, which can subsequently exaggerate animal stress and reduce immune responsiveness. In an all-year-round calving system, such as the one used in the current study, housing animals without mixing age groups is challenging if a small number of calves are born each week (1.8 calves per week in the current study). Pedersen *et al.* (2009) found that groups where calves of different ages were mixed exhibited more than twice the level of respiratory disease and scour, and had significantly lower DLWG, than calves housed in homogenous groups (0.81 ± 0.2 kg/d versus 0.87 ± 0.3 kg/d).

Adequate ventilation should: prevent drafts and build-up of humidity; reduce stagnant air and gases; maintain optimum temperature and humidity; decrease dust contamination; and reduce level of airborne bacteria (Callan and Garry, 2002; Earley *et al.*, 2004). By doing so, pathogenic exposure can be reduced

when more vulnerable younger calves are in contact, or sharing air space, with older animals.

Efficient ventilation is particularly important when weaning and re-grouping calves. This is reflected in the highest incidence of respiratory disease between 30 days and 6 months of age, with 95% of treated heifers requiring treatment in this age range. The process of weaning and grouping calves that occurs between 30 days and 6 months of age is often stressful due to social, management and nutritional changes which take place (Callan and Garry, 2002; Bach *et al.*, 2010). This perhaps explains why heifers born in summer had a greater number of BRD treatments. BRD transmission rate can be reduced around weaning by optimising contributing factors such as animal density, housing facilities and ventilation.

5.4.3.1 Housing

Housing pre-weaned calves in hutches, as used in the current study, has been demonstrated to improve calf health (Quigley *et al.*, 1994a; Earley *et al.*, 2004). Individual hutches, correctly spaced 4 metres apart, effectively reduce aerosol transmission of respiratory microbes (Mars *et al.*, 2000). A Minnesota study reported that housing calves individually affected growth rate no differently than immediately grouping calves post-weaning (Ziegler *et al.*, 2008). Solid dividers between individually housed calves are effective in reducing BRD by decreasing pathogenic exchange between pens and preventing direct nose-to-nose contact (Lago *et al.*, 2006). However, Bach *et al.* (2010) found increased growth rate and fewer respiratory treatments in calves weaned and grouped at 49 days, compared with calves housed in individual hutches for one week (BRD incidence: 20% versus 34%). There is an argument that adverse weather conditions and colder temperatures can compromise management of calves housed outdoors as extra energy is required at a lower critical temperature of 10 to 15° C in the first two weeks of life and 6 to 10 °C after this (Davis and Drackley, 1998; Webster, 2019). Greater nesting scores, associated with straw bedding, as used in the current study, are related to reduced BRD incidence (Lago *et al.*, 2006). If calves are housed in groups, then replacing bedding frequently to reduce contact with faeces from other calves is recommended to

decrease scouring (Cho and Yoon, 2014). The ability to nest decreases a calf's lower critical temperature, eliminating the additional energy requirement for cold environments (Lago *et al.*, 2006).

Where calves are housed together, the optimum number of animals per group is debated (Maatje *et al.*, 1993; Wells *et al.*, 1996; Svensson *et al.*, 2003). A study on 9 commercial dairy farms in Sweden, assessing morbidity and growth rate of calves housed in groups of 6 to 9, verses 12 to 18 (Svensson and Liberg, 2006), found that calves kept in the smaller groups had lower incidence of BRD and grew at a faster rate than calves kept in the larger groups, which was thought to be due to decreased stocking density. Other studies have reached similar conclusions (Losinger and Heinrichs, 1997; Svensson *et al.*, 2003; Svensson and Liberg, 2006), which suggests that housing calves in groups of less than 10 is optimum for reducing BRD-related morbidity. This is perhaps a consideration for the current study, in which weaned calves were housed in groups of 12 to 16.

5.4.4 Survivability and subsequent performance

Few studies have documented long-term effects of calfhood BRD, due to the challenges of recording animals over their lifetime, and because many animals with severe BRD are more likely to die or be culled before entering the milking herd. Bach (2011) found that heifers affected by BRD ≥4 had greater odds (OR= 1.87 ± 0.14) of not completing first lactation than their healthy herd mates. Heifers were less likely to remain in the herd after 730 days (24 months) of life when treated for BRD more than once in the first 183 days (6 months) of life than any other disease. This is consistent with Waltner-Toews *et al.* (1986), who found that heifers treated for BRD in the first 90 days of life were 2.5 times more likely to die between 90 days (3 months) of age and calving. The current study showed a conflicting result; heifers with no treatment for BRD performed least successfully, with fewer DIM, earlier culling age, and lower milk yield, compared to heifers that were treated. Examination of when heifers without BRD left the herd showed that 46% left in the first two lactations (23% = first lactation, 23%, second lactation), with 81% of those heifers given no reason for exit. Lifetime performance and exit reasons will be discussed further in Chapter

Eight. Better records of herd exit would improve understating of why untreated heifers left the herd sooner than those treated for BRD. It is possible that exposure to BRD in early calfhood may offer a protective effect in heifers which increases their immunity in adulthood, but this is not evidenced. Another possibility is that BRD has little or no impact on cow performance and there may be other confounding factors with greater influence.

5.4.5 Rearing costs

Economic evaluations are important to appreciate the true implications of calfhood disease. A Dutch study found that 86% of surveyed dairy farms underestimated rearing costs (Mohd Nor *et al.*, 2015a; Mohd Nor *et al.*, 2015b), supporting the need for more work in understanding total costs of rearing heifers. Additionally, some studies reported evidence for long-term benefits of greater investment on heifers, which was recouped in later life (Bach, 2011; Wathes *et al.*, 2014; Boulton *et al.*, 2017). The current study found that a heifer treated for BRD ≥4 times cost £880.41 to rear, an additional 48% of estimated rearing costs when calving at 730 days (24 months). Milk losses are often not considered in economic analyses but, in the current study, were estimated to be 77% of the extra cost, highlighting the value of not delaying entry into the milking herd. Feed costs are the main input for most systems, accounting for between 37% (Boulton *et al.*, 2017) and 73% of rearing costs (Heinrichs *et al.*, 2013), depending on housing and grass utilisation. Considering this and the additional days of feeding over the 730 days (24 months) calving target, rearing costs for heifers receiving ≥4 BRD treatments made up 17% of the final cost, highlighting the inefficiency of feeding non-lactating animals after 730 days of age. Direct costs of BRD treatment (3%) were similar to other studies which included health and disease in their model, ranging from 3.1% (Mohd Nor *et al.*, 2012) to 4.1% (Boulton *et al.*, 2017). Finally, the cost of labour varies considerably among studies, ranging from 9% (Kingshay, 2013) to 32% (Mohd Nor *et al.*, 2012). The current study found additional labour to contribute 3%, which may be an underestimation because only time spent handling animals for treatment was included, and not costs associated with individual management such as extra bedding, assisted feeding, or taking temperatures.

Labour costs associated with other aspects of rearing heifers were already included in rearing costs. Additionally, differences in how youngstock are housed and handled need to be considered in labour costs. Studies reviewed here did not include cost of reduced first lactation milk yield due to disease and delayed AFC, which contributed a large proportion of total costs in the current study. However, it should be noted that estimates in this cost analysis are based on averages e.g. average cost per day or average price of milk, which do not allow for between animal variation. A better understanding of the main factors which affect costs for individual systems is needed for a more accurate and complete evaluation.

5.5 Conclusion

Reducing costs of replacement heifers should be a priority for UK dairy systems. Heifers with no BRD had greater estimated DLWG and met industry calving targets, whereas a significant delay in growth and AFC was found in heifers that received multiple treatments (≥4). This delay costs £880 per heifer in treatment, labour, extra days of rearing and milk losses, increasing estimates of rearing costs by 48%. This study found a positive effect of BRD treatment on subsequent performance and survivability, however, which requires further exploration. Unexpectedly, heifers receiving no treatment had lower lifetime performance, which outweighed savings in rearing costs. Based on findings of this study, BRD prevention is critical in heifer management to reduce calf-hood morbidity, achieve early AFC, and avoid additional rearing costs. This study highlighted that heifers between 30 days and 6 months of age received most BRD treatments between December and February, therefore focusing on prevention methods to minimise incidence at weaning and during the winter period would be most effective.

Chapter 6

Is delayed calving age a result of herd management or heifer fertility?

6.1 Introduction

Fertility has become an important issue for dairy systems in recent decades (Walsh *et al.*, 2011). Genetic selection for milk yield increased productive potential of dairy cows considerably (Tsuruta *et al.*, 2005), but emphasis on selection for milk yield negatively impacted genetic merit for fertility. Average conception rate (CR) for UK herds was around 60% in the 1970s and decreased to 40% in the 1990s (Royal *et al.*, 2000), and to 35% in 2019 (Hanks and Kossaibati, 2019). Likewise, just over half of cows culled in the 1990s had completed a fourth lactation (Esslemont and Kossaibati, 1997), but more recent records show average longevity dropped to 2.8 lactations in 2005 (Tsuruta *et al.*, 2005). Introduction of a genetic index for fertility in 2003 reversed the genetic trend for poor fertility (Winters, 2021), and average longevity increased to 3.6 lactations in 2019 (Hanks and Kossaibati, 2019). Nevertheless, poor fertility remains a major reason for culling, responsible for one in three culls (Ansari-Lari *et al.*, 2012), and increases replacement rate because of reduced CR and herd survivability.

The likelihood of replacement heifers surviving beyond their first lactation and becoming profitable reduces as age at first calving (AFC) increases (Wathes *et al.*, 2008; Sherwin *et al.*, 2016). As a result of poor fertility, delayed AFC and a short productive life come at a significant economic cost to dairy systems, and the demand to replace these animals puts increasing pressure on heifer rearing management.

This study aimed to evaluate the effect of heifer fertility on AFC, subsequent performance, and herd longevity. The hypothesis was that heifers with greater days between first service and successful service (diagnosed pregnant) take longer to conceive in first lactation, leave the herd earlier, and consequently spend a smaller proportion of their life lactating, thus reducing herd efficiency.

6.2 Material and Methods

6.2.1 Animals and location

This was a retrospective study carried out using data from Holstein-Friesian heifers born at the Nottingham University Dairy Centre between 2007 and 2018. Heifers were selected if they had a recorded date of successful service (diagnosed pregnant) and recorded date of first calving (n=852).

6.2.2 Management

All animals were fed and housed as described in 2.2 Youngstock management and 2.3 Adult cow management, and mated as described in 2.4 Heifer and cow reproduction.

6.2.3 Data collection

Data were extracted from the herd management database (Uniform-Agri Professional, UK) using Microsoft SQL Server Management Studio database software linked to the lactating cow software (Time4Cows; T4C, Lely Ltd., UK).

Microsoft SQL was used to extract historic data for date of first service and date of successful service (diagnosed pregnancy (PD+)); AFC; live weight (LW); milk yield, days in milk (DIM) and dry-off date per lactation; and culling date. LW was measured using load cells fitted to the automatic milking system (AMS; Lely Astronaut A3, Lely Ltd., UK). An average herd mature weight (MW) for each year of birth was calculated as mean LW of cows in ≥3 lactations and between 100 and 200 DIM and used to calculate target LW at first service of 55% and LW at first calving (LWFC) of 85% MW. Estimated daily LW gain (DLWG) from birth to first calving was calculated by dividing LWFC minus 45 kg (assumed birth weight (Archer, 2021)) by AFC; and first lactation DLWG was calculated as difference between first and second calving LW, divided by first lactation calving interval.

Heifer performance data were analysed in 852 heifers. Data were examined were number of services; CR; age at first service (AFS) and age at service

resulting in PD+; days to first service (days between first calving and first service), days to conceive (days between first service and service resulting in PD+); estimated maturity at first service and at service resulting in PD+ (age at first service and at service resulting in PD+ multiplied by estimated DLWG and divided by herd MW at year of birth); and age and maturity at first calving. CR was calculated for individual heifers and defined as reciprocal of number of services, i.e., 1 serve =100%, 2 serves = 50%, 3 serves = 33% etc.

First lactation performance data were analysed in 684 cows that calved for a second time, this excluded 168 cows that calved only once from the dataset. Data examined were first lactation DIM, calving interval, and milk yield; LW gain between first and second calving, and as a proportion of first calving LW; number of services; CR; age at first service and at service resulting in PD+; and days to conceive and to second conception (days between AFC and service resulting in PD+).

Lifetime performance data were analysed from 651 cows that had been culled at time of analysis. Data examined were lifetime milk yield, lifetime DIM, lifetime daily yield (LDY; lifetime milk yield divided by culling age), days spent unproductive (AFC plus dry days), culling age (days), lactation of culling, days in profit, profitable life and productive life. Days in profit was defined as number of days exceeding breakeven age, where breakeven age was calculated as the age at which a heifer returns her rearing costs ((AFC plus 530 days (Boulton *et al.*, 2017)) with negative values adjusted to 0. Profitable life was defined as the proportion of life spent in profit (days in profit divided by culling age) and productive life was defined at the proportion of life spent lactating (lifetime DIM divided by culling age).

6.2.4 Statistical analysis

Data were collated using Microsoft Office Excel (2016) and analysed using GenStat (21st edition; VSN International, UK). Data were grouped according to heifer fertility performance, which was defined by days between first service and service resulting in PD+; Excellent: 0 days, Good: 1 to 25 days, Fair: 26 to 50 days and Poor: ≥50 days. Data for heifer, first lactation and lifetime

performance were analysed using Generalized Linear Models (GLM) with fertility group and year of birth as fixed effects. Normal error distribution was used for CR, LW, DLWG and milk yield data; Poisson error distribution with a log-linear link function was used for count data. This included data comprising days (days to conceive, days to first service, AFC, DIM, days spent unproductive and days in profit) and number of services. For variables with a dispersion parameter below 1, dispersion parameter was fixed at 1, and for variables with a dispersion parameter above 1, dispersion parameter was estimated. Statistical significance is reported at $p<0.05$ and differences between treatments were compared using Bonferroni test with a 95% confidence interval. Means are presented with their standard error (SE) and statistical insignificance is reported as NS.

6.3 Results

6.3.1 Heifer performance

Age at first service was not different between fertility groups, with heifers on average being first served at 445 ± 61 days with an estimated 47.5 ± 6.4% MW, and PD+ at 479 ± 76 days with an estimated 51.0 ± 7.2% MW. On average heifers were served 2.1 ± 1.3 times and had a CR of 66.6 ± 32.0%, but CR decreased as fertility performance decreased because heifers with poor fertility were least likely to be PD+ and required almost 4 services (Table 6.1). This meant heifers with poor fertility were almost 100 days older at service resulting in PD+ and at first calving than heifers with excellent fertility. Consequently, heifers with poor fertility were 6.1% more mature at PD+ and 6.3% more mature at calving than heifers with excellent fertility. AFC increased as heifer fertility decreased with heifers with poor fertility calving 99 days later than heifers with excellent fertility. Heifers with poor fertility were the only group to achieve target mating MW of 55 to 60% but were also the only group to exceed calving targets of 700 to 760 days and 85 to 90% MW at first calving. As a result, heifers with poor fertility were significantly heavier at first calving. There was no difference between fertility groups in estimated DLWG from birth to calving with heifers

growing at 0.74 ± 0.09 kg/d on average. The proportion of heifers to calve a second time reduced with decreasing fertility.

Table 6.1: Mean (standard error) heifer performance data in heifers born between 2007 and 2018 (n=852) according to fertility performance, defined by days between first service and successful service (diagnosed pregnancy); Excellent: 0 days, Good: 1 to 25 days, Fair: 26 to 50 days and Poor: ≥50 days

	Fertility				P
	Excellent	**Good**	**Fair**	**Poor**	
No. heifers	390	143	107	212	
Heifers, %	45.8	16.8	12.6	24.9	
First service:					
Age, days	445 (2.4)	445 (4.2)	441 (4.6)	446 (3.4)	NS
Estimated maturity, %	48.3 (0.28) [b]	47.7 (0.48) [b]	47.1 (0.55) [ab]	45.9 (0.40) [a]	<0.001
Successful service					
Age, days	449 (2.6) [a]	468 (4.6) [b]	485 (5.2) [b]	548 (4.1) [c]	<0.001
Estimated maturity, %	48.3 (0.29) [a]	49.8 (0.50) [ab]	51.4 (0.57) [b]	56.4 (0.41) [c]	0.007
No, services	1.0 (0.05) [a]	2.1 (0.13) [b]	2.5 (0.16) [c]	3.8 (0.14) [d]	<0.001
Conception rate, %[1]	100.0 (0.32) [d]	48.8 (0.55) [c]	42.6 (0.62) [b]	29.2 (0.45) [a]	<0.001
Days to conceive	0 (0.0) [a]	20 (1.0) [b]	40 (1.6) [c]	102 (1.8) [d]	<0.001
First calving					
Age, days	723 (2.6) [a]	742 (4.6) [b]	759 (5.2) [b]	822 (4.0) [c]	<0.001
Maturity, %	85.1 (0.39) [a]	86.2 (0.67) [ab]	87.6 (0.75) [b]	91.4 (0.55) [c]	0.015
Live weight, kg	588 (2.70) [a]	595 (4.62) [ab]	606 (5.21) [b]	631 (3.80) [c]	0.020
Daily live-weight gain, kg/d	0.75 (0.045)	0.74 (0.076)	0.74 (0.086)	0.72 (0.062)	NS
Calved a second time, %	82.6 (1.92) [b]	84.6 (3.01) [b]	78.5 (3.97) [ab]	74.1 (3.01) [a]	0.043

[1]Conception rate was calculated for individual heifers and defined as reciprocal of number of services, i.e., 1 serve =100%, 2 serves = 50%, 3 serves = 33% etc.

[abc] Statistical significance (p<0.05) is reported with different letters

6.3.2 First lactation performance

First lactation cows on average had more services (2.6 ± 1.8) and lower CR (57.9 ± 32.6%) than heifers (Table 6.2). Number of services in first lactation increased with decreasing heifer fertility. Group means were more similar than for heifers, however, despite a greater range (min: 1 service, max: 14 services) than for heifers (min: 1 service, max: 8 services). There was no difference in days to first service between fertility groups and on average first lactation cows were served 56 ± 0.8 days after first calving. Cows with poor heifer fertility took an additional 18 days to conceive from first service in their first lactation, and 21 days from first calving, compared to cows with excellent heifer fertility. As cows with poor heifer fertility were 100 days older at first calving, conception in first lactation was 120 days later in life than cows with excellent heifer fertility. First lactation milk yield increased with decreasing heifer fertility, and cows with poor heifer fertility yielded 911 L more than cows with excellent heifer fertility. LW gain from first to second calving was not different between groups, with cows gaining 82 ± 59 kg (equating to 0.21 ± 0.15 kg/d) on average in their first lactation. However, LW gain in first lactation as a proportion of first calving LW was lower in cows with poor heifer fertility than for cows with excellent heifer fertility. Cows with fair or good fertility as a heifer had similar means for number of services, AFS, age at conception, days to conceive from first service and first calving and first lactation milk yield.

Table 6.2: Mean (standard error) first lactation performance data in heifers born between 2007 and 2018 (n=684) according to days between first service and successful service (diagnosed pregnancy) as a heifer; Excellent: 0 days, Good: 1 to 25 days, Fair: 26 to 50 days and Poor: ≥50 days

	Heifer fertility				P
	Excellent	**Good**	**Fair**	**Poor**	
No. heifers	322	121	84	157	
Age at, days					
First service	779 (3.3) [a]	800 (5.6) [b]	813 (6.6) [b]	879 (5.3) [c]	<0.001
Successful service	821 (4.4) [a]	851 (7.6) [b]	858 (9.0) [b]	940 (7.3) [c]	<0.001
Days to first service	55 (0.99)	58 (1.67)	54 (1.87)	57 (1.40)	NS
No, services	2.3 (0.09) [a]	2.6 (0.16) [ab]	2.5 (0.18) [ab]	3.0 (0.15) [b]	0.046
Conception rate, %[1]	63.6 (1.83) [b]	53.9 (3.1) [a]	56.1 (3.6) [ab]	49.4 (2.8) [a]	<0.001
Days to conceive	42 (3.0) [a]	51 (5.6) [ab]	45 (6.1) [ab]	60 (5.4) [b]	0.021
Days to successful service	97 (3.1) [a]	111 (5.6) [ab]	98 (6.1) [ab]	118 (5.1) [b]	0.007
Milk yield, L	11169 (161) [a]	11948 (270) [ab]	11437 (319) [ab]	12080 (248) [b]	0.023
Days in milk	325 (3.2) [a]	340 (5.5) [ab]	331 (6.4) [ab]	342 (5.0) [b]	0.040
Days dry	49 (1.5)	51 (2.3)	46 (3.0)	51 (1.9)	NS
Calving interval, days	373 (3.3) [a]	394 (5.8) b	377 (6.6) [ab]	394 (5.3) [b]	0.023
Live-weight gain, kg	82 (3.2)	87 (5.4)	81 (6.4)	70 (5.0)	NS
Daily live-weight gain, kg/d	0.22 (0.06)	0.23 (0.10)	0.22 (0.12)	0.18 (0.09)	NS
Live-weight gain, % Live-weight at first calving	14.5 (0.59) [b]	15.5 (0.98) [b]	14.3 (1.16) [ab]	11.6 (0.90) [a]	<0.001
Second calving maturity, %	97.1 (0.48) [a]	98.9 (0.81) [a]	98.9 (0.96) [ab]	102.1 (0.74) [b]	0.033

[1]Conception rate was calculated for individual heifers and defined as reciprocal of number of services, i.e., 1 serve =100%, 2 serves = 50%, 3 serves = 33% etc.

[abc] Statistical significance (p<0.05) is reported with different letters

6.3.3 Lifetime performance

All lifetime performance parameters were affected by fertility group except culling age, where cows were on average 1760 ± 652 days of age when they left the herd (Table 6.3). Cows with excellent heifer fertility yielded most milk during their lifetime, producing 6162 L (2.7 L/d) more than cows with poor heifer fertility. Cows with excellent heifer fertility had 156 more DIM, 150 more days in profit and spent 67 fewer days unproductive over their lifetime than cows with poor heifer fertility. As a result, profitable and productive life decreased with decreasing heifer fertility so that cows with poor heifer fertility spent 6.0% and 3.9% less of their life in profit and lactating respectively than cows with excellent heifer fertility. There was no difference in culling age but cows with excellent heifer fertility completed 0.6 more lactations than cows with poor heifer fertility Cumulative mortality increased at the slowest rate in heifers with excellent fertility (Figure 6.1).

Table 6.3: Mean (standard error) lifetime performance data in heifers born between 2007 and 2018 (n=651) according to fertility performance, defined by days between first service and successful service (diagnosed pregnancy) as a heifer; Excellent: 0 days, Good: 1 to 25 days, Fair: 26 to 50 days and Poor: ≥50 days

	Fertility				P
	Excellent	**Good**	**Fair**	**Poor**	
No. heifers	292	108	76	175	
Lifetime milk yield, L	35647 (1192) [b]	34057 (2063) [ab]	28987 (2358) [a]	29275 (1690) [a]	<0.001
Lifetime days in milk	942 (30.9) [b]	910 (50.7) [ab]	784 (53.9) [a]	786 (36.0) [a]	<0.001
Lifetime daily yield, L/d	17.5 (0.37) [b]	17.5 (0.65) [b]	15.5 (0.74) [ab]	14.8 (0.53) [a]	<0.001
Unproductive days	856 (6.7) [a]	861 (11.6) [a]	862 (13.2) [a]	923 (9.7) [b]	<0.001
Days in profit	614 (33.0) [b]	553 (47.6) [ab]	460 (53.1) [a]	464 (33.5) [a]	0.008
Productive life, %	45.8 (0.91) [ab]	47.3 (1.50) [b]	42.4 (1.79) [ab]	41.9 (1.18) [a]	0.010
Profitable life, %	26.2 (1.26) [b]	24.5 (1.88) [ab]	20.4 (2.07) [a]	20.2 (1.32) [a]	0.006
Lactation of culling	3.2 (0.09) [b]	3.0 (0.15) [ab]	2.7 (0.16) [a]	2.6 (0.11) [a]	<0.001
Culling age, days	1810 (34.1)	1784 (57.6)	1661 (63.4)	1720 (44.6)	NS

[abc] Statistical significance (p<0.05) is reported with different letters

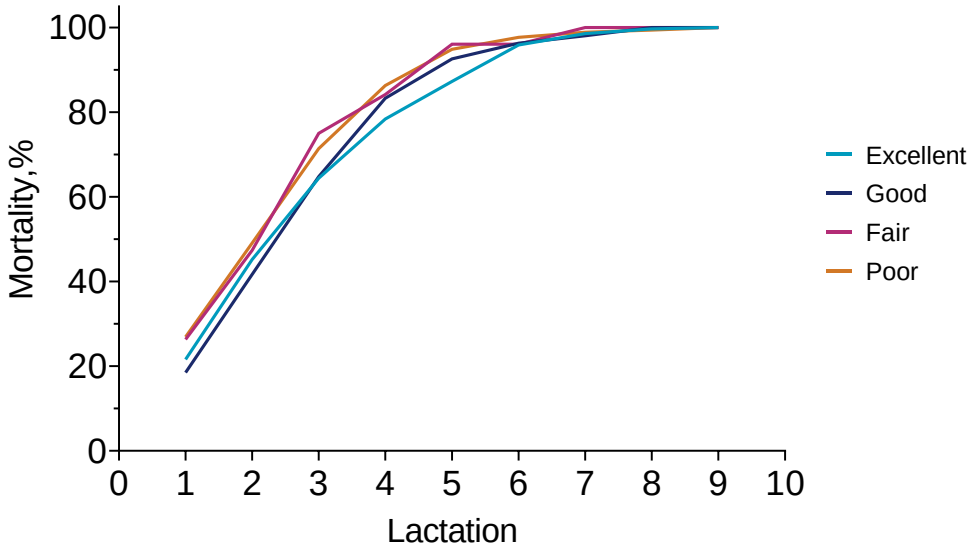


Figure 6.1: Cumulative mortality per parity in heifers born between 2007 and 2018 (n=651) according to fertility performance, defined by days between first service and successful service (diagnosed pregnancy) as a heifer; Excellent: 0 days, Good: 1 to 25 days, Fair: 26 to 50 days and Poor: ≥50 days

6.4 Discussion

This study evaluated the effect of heifer fertility on AFC and lifetime performance. Specifically, the effect of days between first service and conception on first lactation fertility, milk yield and survivability.

The age a heifer enters the milking herd is a key performance indicator in many dairy systems. However, since calving age is a function of age at conception, long tails in this distribution reflect poor fertility in some animals. Age at conception in turn is a function of AFS and CR, of which CR is a good measure of the animal's fertility. AFS is determined by success of the rearing programme which includes when heifers reach puberty plus a management decision on the age to start serving (Hoffman and Funk, 1992). In this study, the mean age at service resulting in PD+ was 479 days (15.7 months) but ranged from 283 to 794 days (9.3 months to 26.1 months). This mean is below the UK mean of 509 days (range 365 to 700 days) at conception (Boulton *et al.*, 2017) but the large variability in the current study meant 62% of heifers failed to calve before 730 days (24 months) of age.

Growth rate has a major influence on heifer fertility, and variability within groups of heifers can lead to a large spread in AFS. Heifers in the current study grew on average at 0.74 kg/d, but this ranged between 0.48 and 1.00 kg/d, which is a similar variability to what Brickell *et al.* (2009) found on one farm (0.45 to 1.15 kg/d). Age at puberty is strongly influenced by DLWG, which in turn is determined by plane of nutrition (Gasser, 2013). Heifers that are underfed have compromised future performance (Van Amburgh *et al.*, 1998; Bach, 2011; Brickell and Wathes, 2011). Heifers might grow slowly due to a less intensive feeding strategy therefore those with poorer fertility may reach puberty later and may either not be fertile or mature enough at first service.

To calve by 730 days (24 months) of age, heifers need to be pregnant by 456 days and may be served from 395 days (13 months). However, studies have shown it is more effective to serve heifers based on maturity, suggesting that 55 to 60% of MW is optimum (Margerison and Downey, 2005). Breed recommendations suggest Holstein types should have LW of 582 kg at calving, which requires an average DLWG of 0.75 kg/d to calve at 730 days (24 months) (Wathes *et al.*, 2008). Even within breeds, MW can vary considerably so ideally LW targets should be based on LW of mature cows in individual herds (Bach and Ahedo, 2008). Over the current study period, all heifers were offered similar diets which were fed to support an average post-weaning growth rate of 0.70 kg/d. However, on average, heifers were first served at 47.5% MW which is 10% below mating target, although heifers conceiving earlier were marginally heavier at first service. This is consistent with Wathes *et al.* (2008) who found that heifers that failed to conceive at 456 days (15 months) were lighter than those that did conceive. In the current study, maturity at first service was estimated from average DLWG between birth and first calving, and it is possible that heifers had a higher DLWG before first service as DLWG is known to decrease after 450 days (14.8 months) of age (Coffey *et al.*, 2006; Brickell *et al.*, 2009a). Additionally, results from Chapter Three show that LW in the study herd increased between 2007 and 2018, therefore 0.7 kg/d may not be an adequate target for these larger Holstein-Friesian heifers, particularly in the latter years. This argument supports the practice of weighing heifers, calculating a herd MW and accurately diet formulation for target growth rates.

Weaning strategy is another key consideration for achieving correct DLWG. Weaning should be based on concentrate intake to ensure adequate rumen development rather than on age or LW (Roth *et al.*, 2009). Unless an animal is ready to transition to a solid diet there will be a growth check at weaning, which may negate any benefit of elevated pre-weaning growth (Khan *et al.*, 2011a) and reduce reproductive development. However, Cooke *et al.* (2013) found that lower DLWG was not always related to plane of nutrition when heifers calved over 913 days (30 months) despite being managed the same as their earlier-calving peers. Such differences may potentially be caused by variations in intake between animals in a group associated with dominance hierarchy. More commonly, however, low DLWG and delayed puberty are associated with calfhood disease, notably bovine respiratory disease and scour (Correa *et al.*, 1988; Bach *et al.*, 2011), and particularly the duration and severity of disease before 183 days (6 months) of age (Donovan *et al.*, 1998b), as discussed in Chapters Four and Five.

In the current study, AFS was not different between fertility groups and heifers were on average 445 days when they were first served. However, estimated maturity at first service was different between fertility groups; heifers with poorer fertility were less mature when first served. This suggests that heifers were first served based on age (around 445 days) and not on MW. This is not uncommon as a Dutch survey found that 60% of dairy farms used age rather than LW to determine first service (Mohd Nor *et al.*, 2013). However, because of poor growth, Cooke *et al.* (2013) found that heifers calving at 913 days (30 months) were deemed too small to mate at 456 days (15 months), and first service was delayed by on average 152 days (5 months). This delay may be acceptable for some AYR calving systems; however, seasonal herds may have to delay serving non-pregnant animals for a whole year.

Heifers with poorer fertility might have lower reproductive efficiency and CR, so required repeat services to conceive. Lower reproductive efficiency may have been due to disease and poor growth. Heifers in the current study had a mean CR of 68% which is consistent with reported averages of 67% (Cooke *et al.*, 2013) for UK heifers but falls to 57% as heifers get older. It has been suggested

that there is a relationship between heifer and cow fertility. Swali (2004) found that first lactation animals which experienced delayed ovulation over more than 45 days after calving required more services as a heifer than those that resumed normal cyclicity (2.7 ± 0.45 versus 1.5 ± 0.11, p<0.01). Wathes *et al.* (2008) found a similar association (1.6 ± 0.09 versus 2.4 ± 0.18 services, p=0.011), which supports that heifers have intrinsically better fertility than first lactation cows. This concurs with the current study as on average heifers had fewer services (2.1 ± 0.05 versus 2.6 ± 0.09) and higher CR (66.6 ± 1.10% versus 57.9 ± 1.25%) than first lactation cows.

Early embryo loss and abortion can contribute to poor pregnancy rate and delayed calving. Although not measured in the current study, it is thought that first pregnancy abortions occur in 1.3% to 4.8% of heifers (Brickell *et al.*, 2009b; Bach, 2011). This can result in either immediate culling, delayed AFC if remating is possible, or premature AFC if gestation was advanced enough to initiate lactation. However, performance gain associated with AFC was negated by subsequent fertility and survival, as heifers were less likely to complete their first lactation following an abortion (Bach, 2011; Cooke *et al.*, 2013). The current study supports this association as likelihood of surviving to second calving reduced as days to conception increased, with one in four heifers with poor fertility not calving for a second time. Additionally, Bach (2011) found that number of services received as a heifer was negatively related to survival, and those completing their first lactation had a first service CR of 60.3% compared to 50.7% in heifers that did not complete their first lactation. Heifers which required more than three services were more likely to leave the herd within 50 DIM.

Heifers with poor fertility had the greatest first lactation yield, producing almost 1000 L more than heifers with excellent fertility. However, this is thought to be related to maturity at calving, which has been associated with first lactation milk yield (Cooke *et al.*, 2013). Coffey *et al.* (2006) found heifers continue to grow into their third lactation, therefore, lighter calving heifers must continue to mature to a greater extent and this nutrient demand for growth may be at the expense of milk production. Nevertheless, Carson *et al.* (2002) found that

although lighter cows at calving produced less milk in the first lactation, they had a shorter calving interval. This equated to lower feed costs and higher net milk value over two lactations.

Older, and more likely overweight, heifers are at greater risk of calving difficulties and not resuming oestrous cyclicity (Bourne *et al.*, 2007). As this was a retrospective study and heifer LW was not recorded over the study period, body condition was not directly recoded. However, in the current study, heifers with poor fertility exceeded the 85 to 90% MW target at first calving. This may be associated with excessive body condition which can further suppress fertility, as heifers with higher body condition at calving mobilise more body tissue (Wathes *et al.*, 2008). Generally, in the current study, days to second service and second calving were higher in cows who took longer to conceive as a heifer. However, first lactation cows that had good fertility as a heifer had the same calving interval as heifers with poor fertility. This perhaps was because heifers with good fertility took longer than expected to conceive and had the greatest number of days dry, which added to the longer interval.

Age at first calving has been associated with subsequent fertility and survivability, with heifers calving between 700 and 760 days having shorter calving intervals (Ettema and Santos, 2004; Eastham, 2012) and greater herd longevity (Bach, 2011; Cooke *et al.*, 2013). Eastham (2012) found that calving interval increased with lactation number, but heifers calving closer to the 730 days (24 months) target had consistently lower calving intervals which were pivotal in maximising lifetime yields. Additionally, Cooke *et al.* (2013) found as AFC increased above 760 days (25 months), proportionately fewer cows achieved a third calving, as 70% of heifers calving between 700 and 760 days (23 and 25 months) reached third lactation compared with only 50% of those calving at 913 days (30 months). Simerl *et al.* (1992) and Evans *et al.* (2006) also found that cows calving at relatively young ages have better survival.

In the current study, culling age was not influenced by fertility and cows were on average 1750 days (4.8 yr) when they left the herd. However, during their lifetime, cows with excellent heifer fertility yielded most milk, producing 6162 L (or 2.7 L/d) more milk than cows with poor heifer fertility. Cows with excellent

heifer fertility cows also spent 156 more DIM, completing an additional 0.6 lactations, and had 67 fewer unproductive days over their lifetime compared to cows with poor heifer fertility. As a result, cows with poor heifer fertility spent 6.5% less of their life lactating and were 18.4% less likely to be profitable than cows with excellent heifer fertility. Together these findings provide strong evidence that it is more economical to rear heifers to conceive at younger ages and with sufficient maturity so that these heifers have a more successful and profitable productive life.

6.5 Conclusion

Good fertility is required to reduce AFC and promote herd longevity, which lowers the non-productive proportion of the herd and improves profit. AFC is influenced by AFS which is a farm management decision, but also the heifer's reproductive biology. This study determined that heifers were first served according to age (mean AFS: 445 days) and not maturity. The results showed that heifers with poor fertility had the lowest estimated maturity at first service (45.9% MW) and required the most serves (3.8). As a result, heifers with poor fertility entered the herd later, took longer to be diagnosed pregnant in their first lactation and spent a smaller proportion of their life lactating. However, this study could not confirm if poor fertility was the result of low maturity at first service and this should be researched further in future studies. Genetic selection has enabled heifers to grow faster and calve before 730 days (24 months) without major adverse consequences. It is therefore important to ensure that these heifers are sufficiently mature at first service to prevent negating performance gains of an earlier entry into the milking herd. Therefore, pre-pubertal growth rate and nutrition are critical for timely puberty and to ensure heifers are pregnant by 395 days (13 months) of age. Calculating LW targets and recording heifer growth would help dairy farmers to optimise heifer management and increase the reproductive success of their replacement programmes. Costs associated with putting sufficient resources into rearing well-grown and healthy heifers will be recouped by producing cows with greater lifetime profitability.

Chapter 7

What challenges do heifers face when they first enter the milking herd? A behavioural approach

7.1 Introduction

A successful transition of replacement heifers into the milking herd is vital if they are to achieve their potential performance and return the investments made during the rearing period. However, a common concern about calving heifers at a younger age, or with smaller body size, is the effect of competition from adult cows which may reduce first lactation performance (Carson *et al.*, 2002).

Cows are herd animals and herd members will form a hierarchy, with first lactation cows most likely to be displaced by mature adult cows due to their younger age and smaller size (Neave *et al.*, 2017). In particular, feeding duration after feed delivery is lowest in newly-introduced cows as competition at the feed bunk is greatest at this time (von Keyserlingk *et al.*, 2008). However, studies have found that differences in systems and management practices can significantly impact individual cow behaviour and performance (Grant and Albright, 2001; DeVries and von Keyserlingk, 2005) Additionally, feeding behaviours, such as daily feeding duration and feeding rate, have been associated with differences in dry matter (DM) intake and feed efficiency (Connor *et al.*, 2013; Halachmi *et al.*, 2016; Xi *et al.*, 2016). Furthermore, improving feed efficiency has been listed as a top three measure to reduce greenhouse gas emissions (Knapp *et al.*, 2014).

Visual observation or video recording have been used to assess cow behaviour. However, automation and precision technologies, such as rumination collars and automated milking and feeding systems, which have become a popular approach to improving overall productivity and efficiency (Bewley *et al.*, 2010), can also be used to assess individual cow behaviour.

There is a lack of comprehensive studies relating feeding behaviour to performance and efficiency of high-yielding dairy cows in automated milking systems (AMS). In conventional milking systems (CMS), where cows may be collected for milking in a parlour up to three times daily, behaviours such as feeding, lying, and ruminating, are organised around timing and duration of parlour milking (Gomez and Cook, 2010). When the constraint of fixed milking times is removed, milking and feeding are more evenly distributed over 24 hrs

(Olofsson *et al.*, 2000), and cows may partition more time to feeding at night than during the day (Helmreich *et al.*, 2014). In both CMS and AMS, however, cows exhibit a degree of synchrony in feeding behaviour when fresh feed is delivered, and when feed is pushed up (DeVries *et al.*, 2003; Deming *et al.*, 2013).

In AMS, cows have greater free choice in organising their time budget, which may influence how first lactation cows behave when they are introduced to adult cows. In practice, first lactation cows have the highest genetic merit in the herd, but 17% of cows do not complete their first lactation and make a positive financial contribution to the herd (Sherwin *et al.*, 2016). Therefore, a better understanding of how high-yielding cows interact in an AMS is needed to support first lactation cows in achieving their potential performance and recouping their rearing costs.

The current study focused on feeding behaviours, particularly daily feeding duration, feeding rate and meal size, of high-yielding cows in an AMS herd between weeks. This study first aimed to compare the behaviour and performance of first parity cows with older parities between one and nineteen of lactation. The second aim of the study looked to compare the behaviour and performance of first parity cows entering the herd with different live weight (LW) and maturity.

7.2 Material and Methods

7.2.1 Animals and location

This study was conducted at the University of Nottingham Centre for Dairy Science Innovation between October 2018 and June 2019. All animal work was conducted under authority of the UK Animal (Scientific Procedures) Act 1986, and ethical approval for this research was obtained from the University of Nottingham Animal Welfare and Ethical Review Board before commencement of the study.

This study comprised additional analysis of data generated in a nutrition experiment involving 54 multiparous high-yielding Holstein-Friesian dairy cows (mean annual milk yield 12,780 L/cow) recorded over the first nineteen WOL. Nutritional treatments were Control versus Yeast supplement, which did not influence feeding behaviour, so all data used in the current study were pooled across treatments. All cows were inspected by the named veterinary surgeon before being assigned to the study at 10 ± 3 days in milk (DIM) and remained for the duration of the study. Cows were selected according to calving date and ranged from lactation 1 to 8; 1 (n = 15), 2 (n = 18), 3 (n = 7), 4 (n = 3), 5 (n = 3), 6 (n = 6), 7 (n = 1) and 8 (n = 1).

7.2.2 Management

All cows were housed and fed as described in Abbreviations: ME: metabolisable energy; MJ: megajoule; DM: dry matter

Cow housing and nutrition from 2018 onwards.

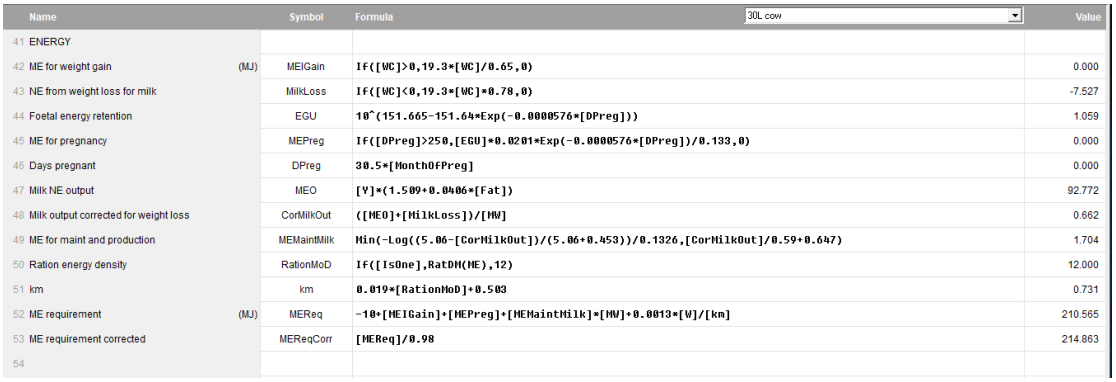
7.2.3 Data Collection

7.2.3.1 Feed intake

Partial mixed ration (PMR) was offered daily, and individual intake was recorded via automated feed bins (Roughage Intake Control System, Hokofarm Group, Netherlands). There were 32 automated feed bins shared between 50 cows and, on average, each cow had access to 16 bins. Each bin was equipped with an electric animal identification system, which recognised the radio-frequency identification tag fitted to every cow and allowed cow entry. Feed intake data were recorded at each entry to the automated feed bins. Data included cow identification number; bin number; date, start and end time of each meal; and weight of PMR in the bin at the start and end of each entry which was used to calculate intake per entry. The entire time spent at the feed bin was considered, whether a cow was eating whilst at the bin or not.

During milking, a compound pellet (robot concentrate) was offered in the AMS. Intakes of PMR and robot concentrate were multiplied by their respective dry matter (DM) contents and combined to calculate total daily DM intake (DMI) and

calculate DMI as a proportion of LW. Energy requirement was calculated in the Ultramix diet formulation programme (AGM Systems Ltd., Romsey, UK) which incorporates ME equations of the Feed into Milk (FiM) feeding system for dairy cows (Thomas, 2004).



	Name		Symbol	Formula (30L cow)	Value
41	ENERGY				
42	ME for weight gain	(MJ)	MEIGain	If([WC]>0,19.3*[WC]/0.65,0)	0.000
43	NE from weight loss for milk		MilkLoss	If([WC]<0,19.3*[WC]*0.78,0)	-7.527
44	Foetal energy retention		EGU	10^(151.665-151.64*Exp(-0.0000576*[DPreg]))	1.059
45	ME for pregnancy		MEPreg	If([DPreg]>250,[EGU]*0.0201*Exp(-0.0000576*[DPreg])/0.133,0)	0.000
46	Days pregnant		DPreg	30.5*[MonthOfPreg]	0.000
47	Milk NE output		MEO	[Y]*(1.509+0.0406*[Fat])	92.772
48	Milk output corrected for weight loss		CorMilkOut	([MEO]*[MilkLoss])/[MW]	0.662
49	ME for maint and production		MEMaintMilk	Min(-Log((5.06-[CorMilkOut])/(5.06+0.453))/0.1326,[CorMilkOut]/0.59+0.647)	1.704
50	Ration energy density		RationMoD	If([IsOne],RatDM(ME),12)	12.000
51	km		km	0.019*[RationMoD]+0.503	0.731
52	ME requirement	(MJ)	MEReq	-10+[MEIGain]+[MEPreg]+[MEMaintMilk]*[MW]+0.0013*[W]/[km]	210.565
53	ME requirement corrected		MEReqCorr	[MEReq]/0.98	214.863
54					

Figure 7.1: Metabolisable energy requirement equations calculated in the Ultramix diet formulation programme (AGM Systems Ltd., Romsey, UK). Values based on a Holstein-Friesian cow producing 30 L/d.

Feeding samples and analysis

Samples of robot concentrate and individual components of the PMR (minimum 2 kg fresh matter of grass silage, maize silage, whole crop silage and concentrate blend) were collected weekly and analysed for determination of DM, crude protein (Nitrogen x 6.25), ash, neutral detergent fibre (NDF), starch, sugars, and fat (oil acid hydrolysis, OAH), using methods determined by the Association of Official Analytical Chemists (AOAC, 1995). Fresh feeds were weighed, oven-dried for >48 hr at 80°C, cooled in a desiccator and reweighed to calculate DM content. Following this, feed samples were ground (1mm) and analysed for crude protein using the Kjeldahl method (method 984.13), NDF using filtration methods developed by Gerhardt (Gerhardt Analytical Systems, Königswinter, Germany) and ash by heating to 600°C for 8 hrs (AOAC, 1990). Chemical composition of the diet is provided in Table 2.4.

7.2.3.2 Feeding behaviour

Feed data recorded by the automated feed bins, as described in Feed intake, was downloaded from the feeding system database (Ceres RIC & HK20.20 Process Controller, Hokofarm Group, Netherlands) and used to calculate

feeding behaviours. Feeding behaviours included daily PMR intake (kg DM/d), feeding duration (min/d); feeding rate (kg DM/min); daily meal frequency; and meal intake (kg DM), duration (min), and time of day when meal started. A 'meal' was defined as the duration the cow visited the feed bin and included her 'non-feeding intervals' between visits, where visits separated by more than 20 min were considered a new meal (Proudfoot *et al.*, 2009). Timing of meals were grouped into three intervals: feed delivery (0730 to 1030 hrs), daytime (1030 to 1930 hrs) and night-time (1930 to 0730 hrs).

7.2.3.3 Rumination and activity

Rumination and activity data were recorded using collar-mounted QWES-HR tags (SCR Engineers Ltd., Netanya, Israel) worn around the neck of each cow. These electronic tags detected rumination sounds through a microphone that separated eating sounds from the rhythmic sound of rumination to calculate minutes spent ruminating. Cow activity was recorded by accelerometers within the same tags, which measured the frequency of electronic impulses through changes in head and neck movements to calculate a general activity index. Rumination and activity data were stored in two-hour blocks and were downloaded each time a cow visited the AMS. Rumination data are presented as minutes per day spent ruminating, and activity data are presented as the daily mean activity index, where a higher numerical value of activity indicated greater cow activity.

7.2.3.4 Milk yield and live weight

Milking data were recorded automatically at each visit to the AMS (Lely Astronaut A5; Lely Ltd., UK). For this study, cow identification number, date, and start and end time of the milking visit were used. Daily milk yield was measured for each cow via the AMS and used to calculate mean yield across seven days for each week of lactation (WOL). Energy corrected milk yield (milk yield corrected for fat and protein concentrations) was calculated using the equation (1.033 x milk yield x [Fat% x 0.383 + Protein% x 0.242 + 0.7832] / 3.1138). Live weight (LW) was measured at each visit using load cells fitted to the AMS and used to calculate a mean LW for each WOL. Calving LW was

recorded from the first visit to the AMS on the first DIM. LW nadir was recorded as the days between calving and the lowest recorded LW, daily LW gain (DLWG) was averaged from weekly DLWG calculated as the difference in weekly LW divided by seven, and net LW gain was the difference between the minimum LW in the first six WOL and average LW in weeks 16 to 19.

7.2.4 Statistical analysis

Data were collated in Microsoft Office Excel (2016) to calculate means for each WOL and analysed using GenStat (21st edition; VSN International, UK). Any day in which daily intake was recorded as '0' was removed. Data were analysed according to Parity: 1 (n=15), 2 (n=18) and ≥3 (n=21). Linear Mixed Models (LMM) were used to investigate effect of parity and WOL on feed intake and behaviour. Parity (1 to 3) and WOL (1 to 19) were used as fixed effects, individual cow was used as a random effect. Data for feed intake, behaviours, rumination, activity, LW and milk yield were analysed using residual maximum likelihood models with Normal error distribution. Meal frequency was analysed using Generalized Linear Mixed Models with Poisson error distribution and a log-linear link function. First calving age and LW, LW nadir and net LW gain were analysed using General Linear Models, where age (days) had Poisson error distribution with a log-link function, LW had Normal error distribution, and Parity was included as a fixed effect. Data for DMI, milk yield and LW change, which might be influenced by calving LW, were subjected to further analysis by adding calving LW as a covariate to the fixed effects. To investigate the effect of LW at first calving (LWFC) on feed intake and behaviour, a subgroup analysis of Parity 1 cows on the current study (n=15) was conducted according to LWFC: <605 kg (n=5), 605 to 665 kg (n=5) and >665 kg (n=5), using LMM with LWFC and WOL as fixed effects and individual cow as a random effect.

Significance was declared at $p<0.05$, and statistical insignificance is reported as NS. Tabulated means are presented with standard error (± SE) according to Parity, and differences between means were assessed using Bonferroni test, with a confidence interval of 95%. Figurative means are presented with SE and differences between means were assessed using Fisher's unprotected LSD test, with a confidence interval of 95%.

7.3 Results

7.3.1 Dry matter intake

Total DMI was lower in Parity 1 cows compared to Parity 2 and Parity ≥3 cows (Table 7.1), mainly because Parity 1 cows consumed less PMR DM than Parity 2 and ≥3 cows for all WOL (Figure 7.2a). Robot concentrate DMI was lower in Parity 1 for some WOL (Figure 7.2b) with Parity 2 cows consuming the most robot concentrate overall. DMI as a proportion of LW was lower for Parity 1 cows than Parity 2 and ≥3 cows, and Parity 1 cows consumed the smallest proportion for most WOL (Figure 7.2d). PMR and total DMI, and DMI as a proprtion of LW were affected by calving LW, however robot concentrate DMI was not (abc Statistical significance ($p<0.05$) is reported with different letters

Table 7.2).

Table 7.1: Mean (standard error) feed intake and energy requirement in the first nineteen weeks of lactation according to parity

	Parity			P
	1	2	≥3	
No. of cows	15	18	21	
Dry matter intake, kg/d				
Partial mixed ration	13.8 (0.48) [a]	18.0 (0.44) [b]	18.2 (0.40) [b]	<0.001
Robot concentrate	6.2 (0.27) [a]	7.2 (0.24) [b]	6.8 (0.22) [ab]	0.024
Total	20.0 (0.52) [a]	25.3 (0.47) [b]	25.0 (0.44) [b]	<0.001
% Live weight	3.0 (0.07) [a]	3.2 (0.06) [b]	3.3 (0.06) [b]	0.048
Energy requirement, ME MJ/d	276 (8.2) [a]	335 (7.4) [b]	340 (6.9) [b]	<0.001
ME intake, % ME requirement	92.7 (3.15)	101.0 (2.88)	96.5 (2.67)	NS

[abc] Statistical significance ($p<0.05$) is reported with different letters

Table 7.2: Mean (standard error) feed intake in the first nineteen weeks of lactation, adjusted for calving live weight, according to parity

	Parity			P
	1	2	≥3	
No. of cows	15	18	21	
Dry matter intake, kg/d				
Partial mixed ration	15.4 (0.58) [a]	17.7 (0.40) [b]	17.5 (0.41) [b]	<0.001
Robot concentrate	6.2 (0.37) [a]	7.2 (0.25) [b]	6.7 (0.26) [ab]	NS
Total	21.6 (0.64) [a]	24.9 (0.44) [b]	24.2 (0.45) [b]	<0.001
% Live weight	2.9 (0.09) [a]	3.3 (0.06) [b]	3.3 (0.06) [b]	0.013

[abc] Statistical significance ($p<0.05$) is reported with different letters

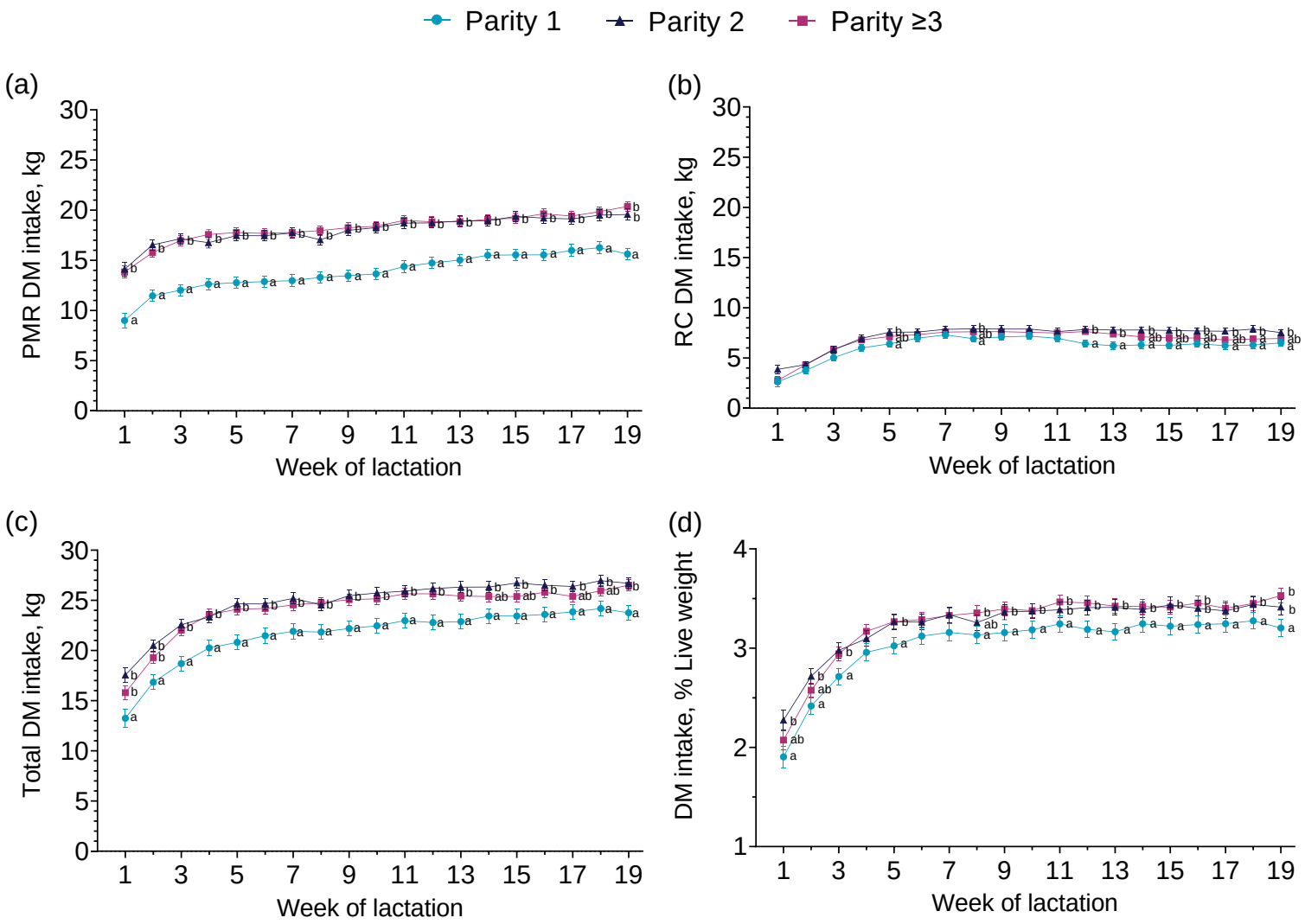


Figure 7.2: Mean (standard error) dry matter (DM) intake of (a) partial mixed ration (PMR), (b) robot concentrate (RC) and (c) total DM intake, and (d) DM intake as proportion of live weight in first nineteen weeks of lactation, according to parity**.**
abc Statistical significance (p<0.05) is reported with different letters

Parity 1 cows required less ME (276 MJ/d) than Parity 2 (335 MJ/d) and ≥3 cows (340 MJ/d; Table 7.1), and a lower ME requirement was consistent until week 18 of lactation (Figure 7.3a). Overall ME intake as a proportion of energy requirement did not differ between parities (Table 7.1). Cows on average consumed 97.5 ± 15.7% of their requirement, although the proportion increased throughout the study (Figure 7.3b), with Parity 2 cows consuming a greater proportion than Parity 1 and ≥3 cows in the first three WOL.

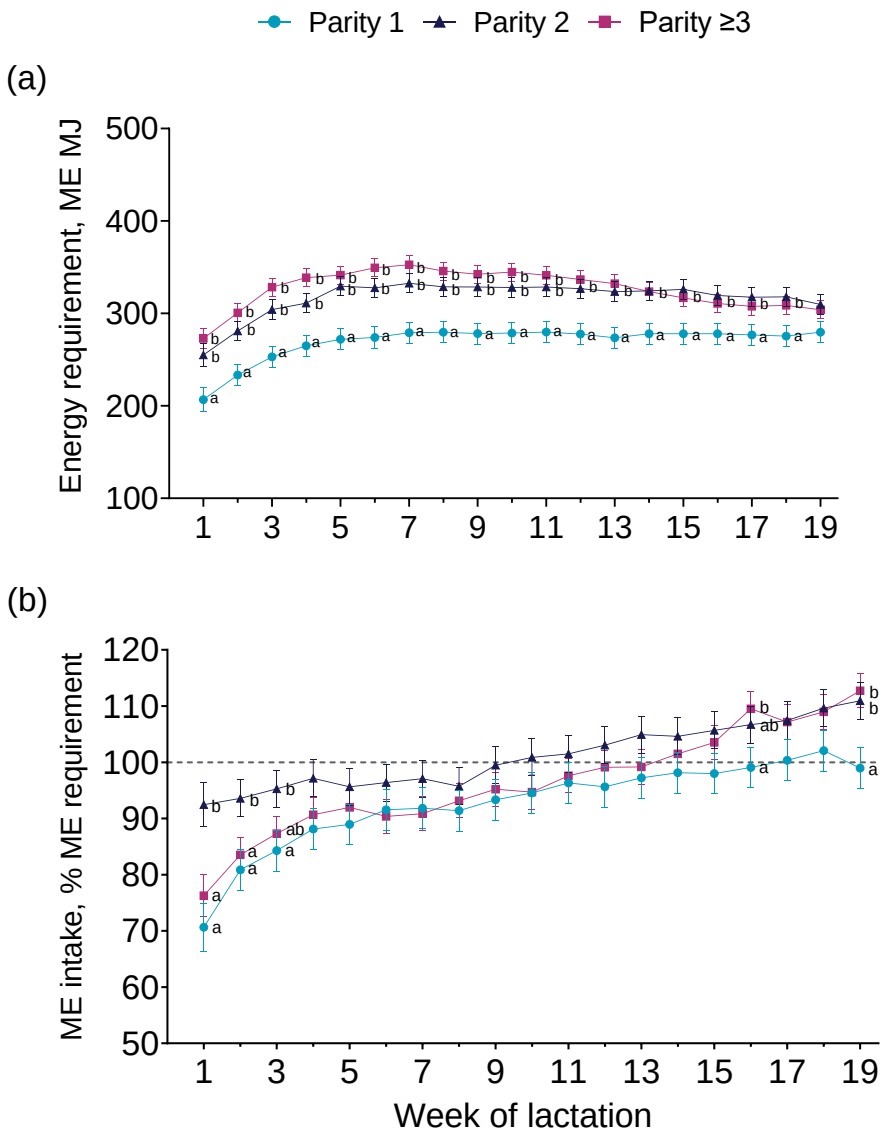


Figure 7.3: Mean (standard error) metabolisable energy (ME) requirement (a) and ME intake as a proportion of ME requirement (b) in first nineteen weeks of lactation according to parity.
abc Statistical significance (p<0.05) is reported with different letters

7.3.2 Behaviour

Parity 2 cows consumed more meals than Parity 1 and ≥3 cows (Table 7.3), although differences were only significant for some WOL (Figure 7.4a). Overall meal duration was not different between parities, and on average cows spent 27 ± 8.1 mins consuming a meal (Table 7.3). However, for some WOL Parity ≥3 cows consumed longer meals than Parity 1 and 2 cows (Figure 7.4b). DMI per meal was associated with both Parity and WOL, and increased steadily throughout the study for all parities. However, Parity 1 cows consumed less than Parity ≥3 cows for most WOL (Figure 7.4c). Overall feeding rate was not different between parities, and on average cows ate at 0.21 ± 0.06 kg/min (Table 7.3). However, feeding rate differed between parities after week 10 of lactation when Parity 2 and ≥3 cows ate faster than Parity 1 cows (Figure 7.4d).

Table 7.3: Mean (standard error) feeding behaviour and daily time budget in the first nineteen weeks of lactation, according to parity

	Parity			P
	1	2	≥3	
No. of cows	15	18	21	
Feeding behaviour				
Meal frequency, no./d	7.3 (0.24) [a]	7.9 (0.22) [b]	7.2 (0.20) [a]	0.029
Meal duration, min	23.9 (1.62)	25.1 (1.48)	28.6 (1.37)	NS
Meal size, kg DM	2.0 (0.11) [a]	2.4 (0.10) [b]	2.7 (0.09) [b]	<0.001
Feeding rate, kg/min	0.19 (0.13)	0.22 (0.12)	0.22 (0.11)	NS
Meal timing, %				
0730 to 1030 hrs	23.4 (0.85)	23.3 (0.78)	24.4 (0.72)	NS
1030 to 1930 hrs	47.1 (1.44)	46.8 (1.31)	47.5 (1.21)	NS
1930 to 0730 hrs	29.4 (1.63)	29.8 (1.48)	28.1 (1.37)	NS
Time budget				
Feeding duration, min/d	167 (8.7)	190 (7.9)	193 (7.3)	NS
Rumination, min/d	456 (8.8)	485 (8.0)	472 (7.4)	NS
Activity, index	49.6 (1.91)	46.7 (1.74)	48.17 (1.64)	NS
Milking frequency, no./d	2.8 (0.13)	3.0 (012)	2.9 (0.11)	NS

[abc] Statistical significance (p<0.05) is reported with different letters

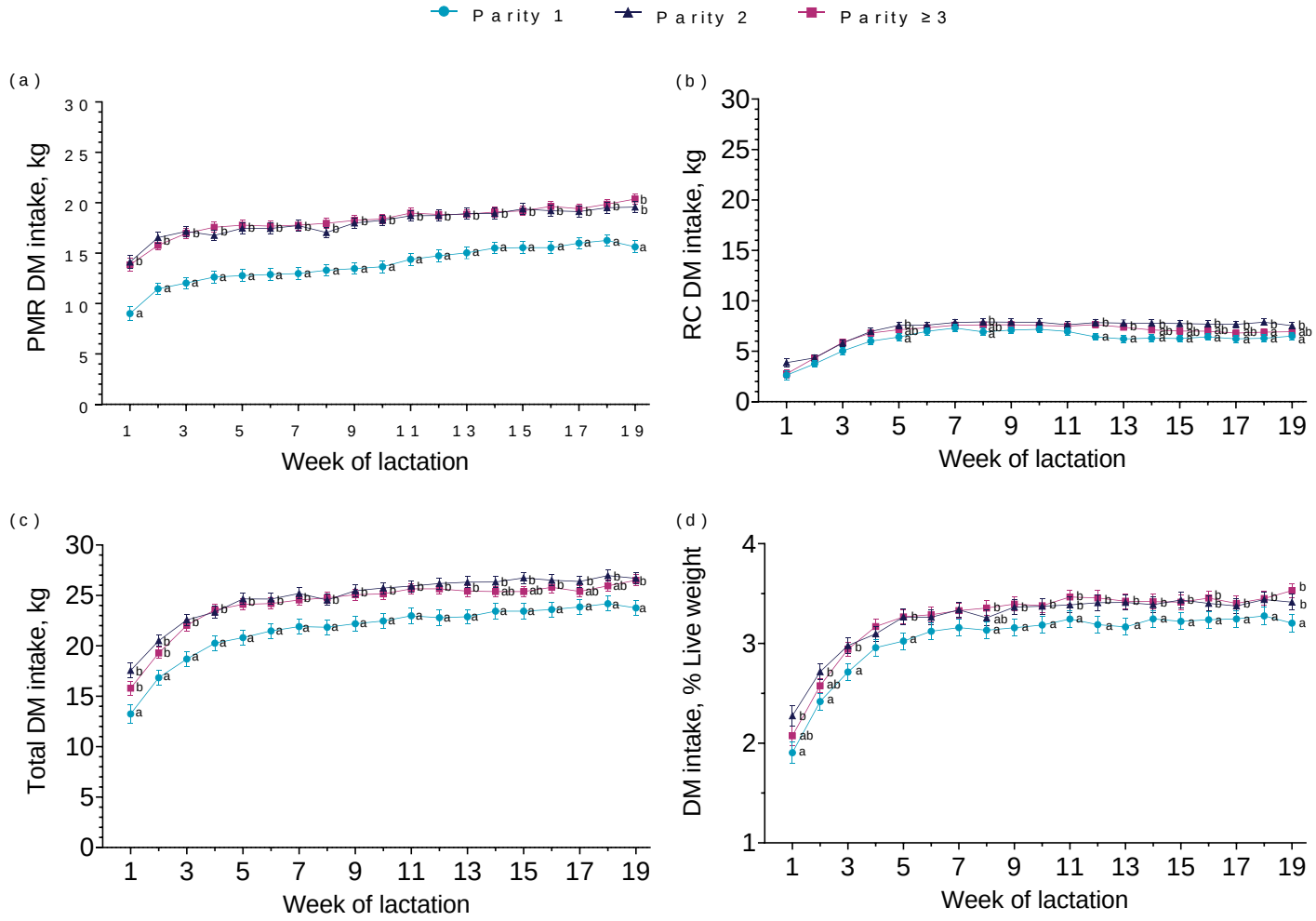


Figure 7.4: Mean (standard error) feeding behaviours; (a) meal frequency, (b) meal duration, (c) meal dry matter (DM) intake and (d) feeding rate in first nineteen weeks of lactation, according to parity.
abc Statistical significance (p<0.05) is reported with different letters

7.3.2.1 Meal timing

Proportion of PMR intake consumed in the three time periods was not different between parities. On average, cows consumed 25 ± 6.0% of PMR during feed delivery, 47 ± 7.8% during daytime, and 29 ± 8.5% during night-time (Table 7.3). However, there were differences during feed delivery where Parity ≥3 cows consumed less than Parity 1 and 2 cows in week 1 and then more than Parity 1 and 2 cows between weeks 2 and 4 (Figure 7.5a). Additionaly, Parity ≥3 cows consumed more than Parity 1 and 2 during daytime in the first WOL (Figure 7.5b).

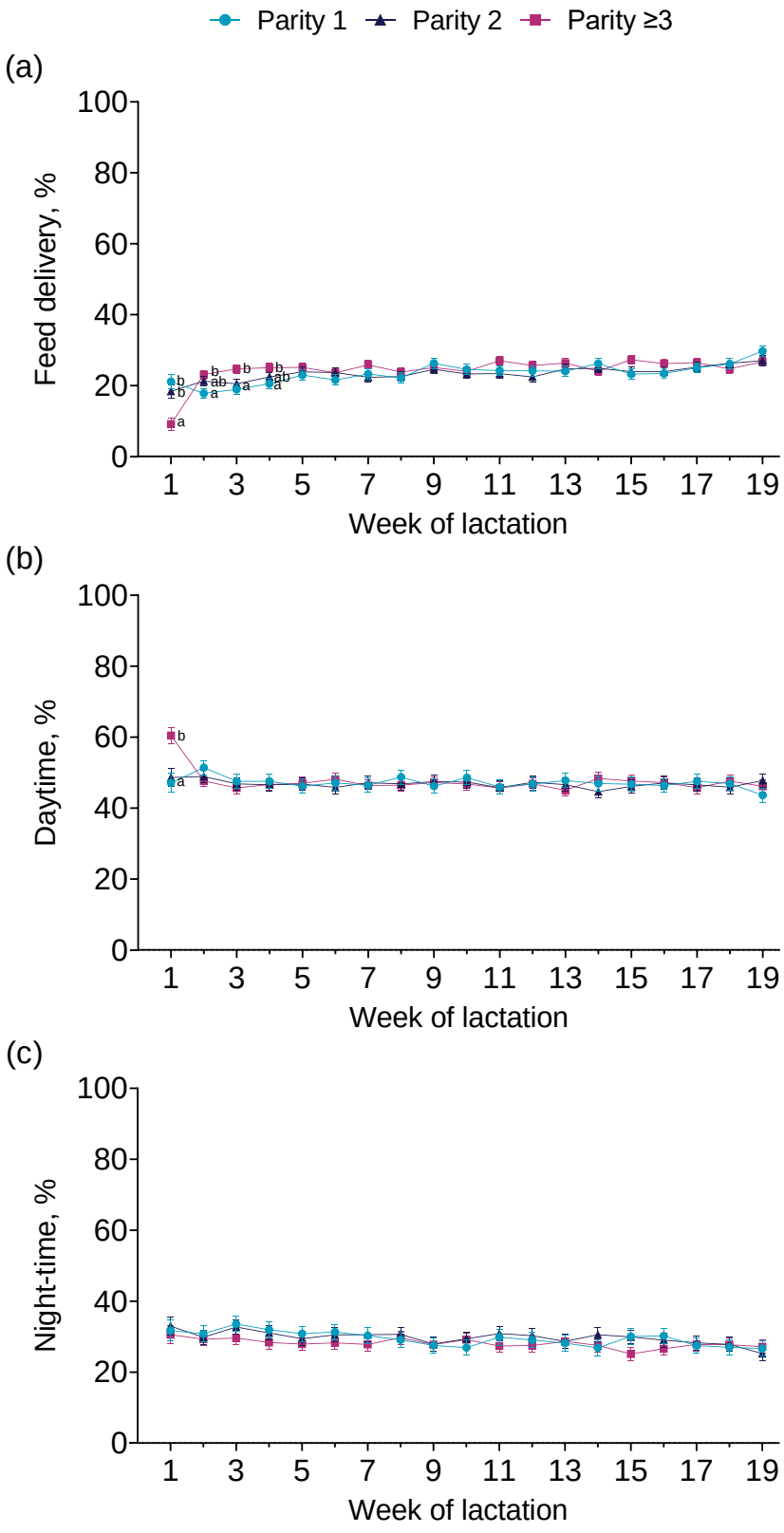


Figure 7.5: Mean (standard error) proportion of partial mixed ration consumed during (a) feed delivery (0730 to 1030 hrs), (b) daytime (1030 to 1930 hrs) and (c) night-time (1930 to 0730 hrs) in first nineteen weeks of lactation
abc Statistical significance (p<0.05) is reported with different letters

7.3.2.2 Daily time budget

Mean daily rumination and feeding duration were not different between parities. On average cows ruminated for 473 ± 44 min/d and ate for 188 ± 43 min/d (Table 7.3). Between weeks 2 and 9 of lactation, Parity 1 cows ate for less time than Parity 2 and ≥3 cows (Figure 7.6a), but between weeks 11 and 19, there was no difference between parities. Parity 1 cows ruminated for less time than Parity 2 and ≥3 cows between weeks 1 and 7 (Figure 7.6b). Time spent feeding and ruminating accounted for 45.8% of an average cow's daily time budget.

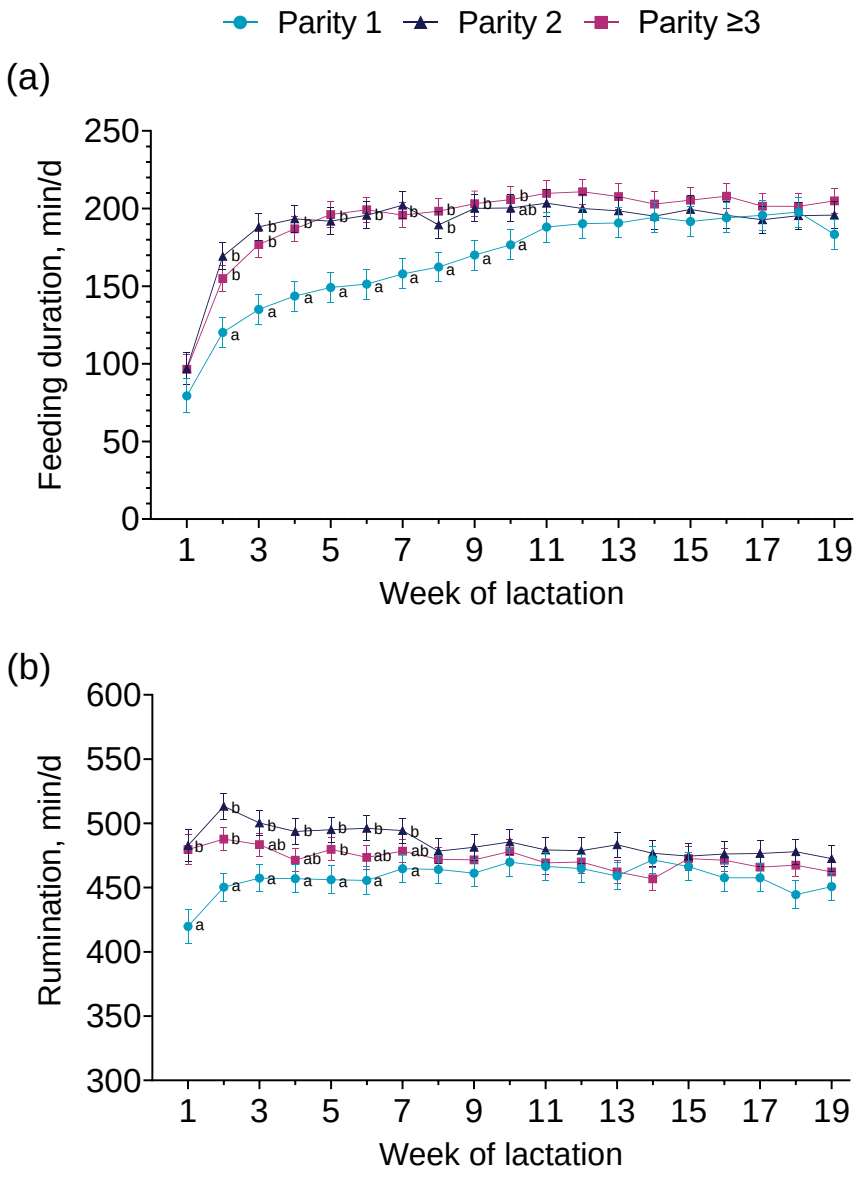


Figure 7.6: Mean (standard error) feeding duration (a) and rumination (b) in first nineteen weeks of lactation, according to parity.
[abc] Statistical significance (p<0.05) is reported with different letters

Mean activity index and milking frequency were not different between parities, and on average cows had an activity index of 47.8 ± 8.3 (range: 22.8 – 94.7) and milked 2.9 ± 0.7 times per day (range: 1.7 – 4.9) (Table 7.3). Parity 1 cows were more active than Parity 2 and ≥3 cows in weeks 1 and 2 of lactation (Figure 7.7a). Weekly averages for daily activity index reported in two-hour blocks varied from 22.8 (low activity) to 94.7 (high activity). Cows in Parity 1 had fewer milking visits than cows in parities 2 and ≥3 in weeks 1 and 2 (Figure 7.7b).

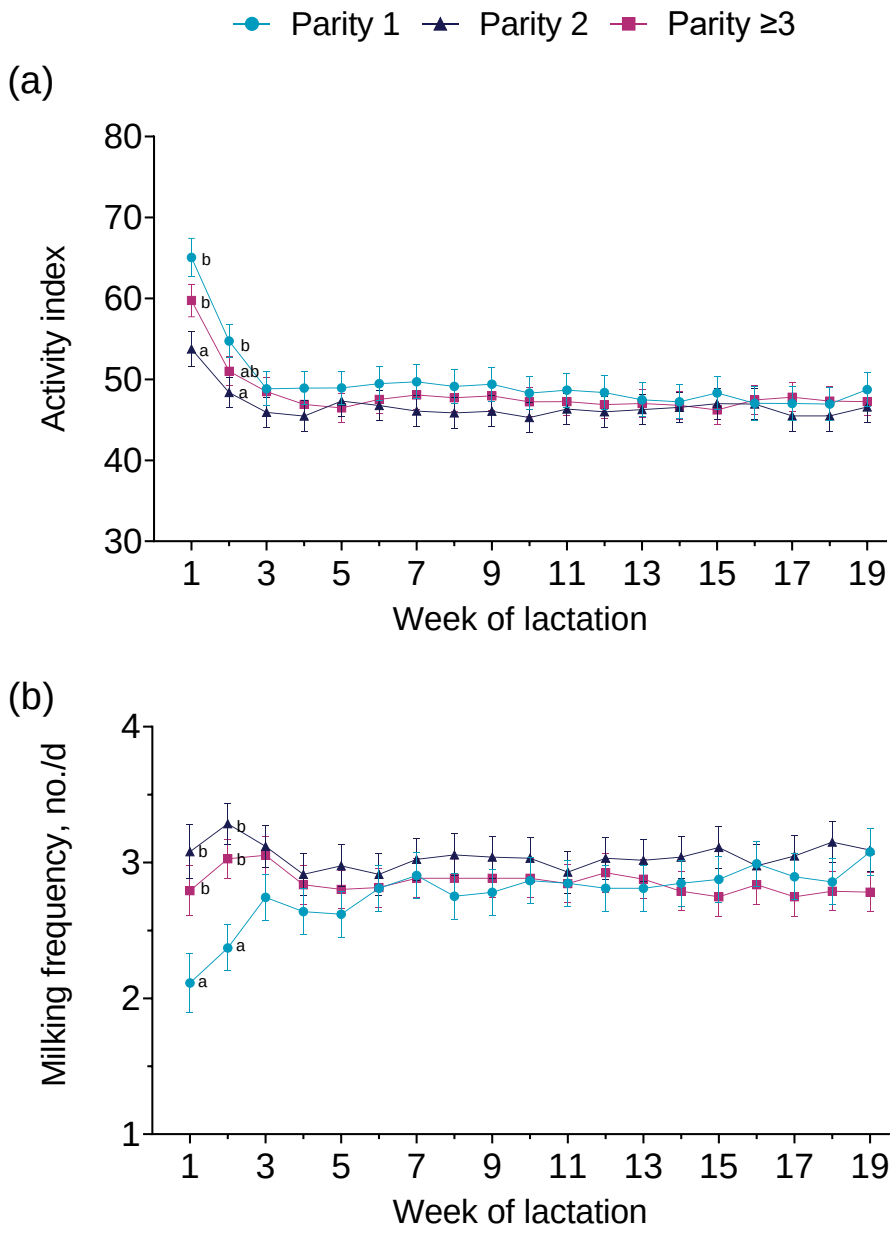


Figure 7.7: Mean (standard error) activity index (a) and milking frequency (b) in first nineteen weeks of lactation, according to parity.
[abc] Statistical significance (p<0.05) is reported with different letters

7.3.3 Milk yield and live weight

All performance parameters differed between parities (Table 7.4). Parity 2 cows were oldest at first calving, followed by Parity ≥3 cows and Parity 1 cows, and LW and maturity at first calving were negatively associated with increased parity (Table 7.4).

Table 7.4: Mean (standard error) of first calving parameters, milk yield, live weight, and live-weight change in first nineteen weeks of lactation, according to parity

	Parity			P
	1	2	≥3	
No. of cows	15	18	21	
First calving				
Age, days	745 (15.9) [a]	832 (15.3) [b]	759 (13.5) [a]	<0.001
Live weight, kg	643 (13.7) [b]	641 (12.5) [b]	574 (11.6) [a]	<0.001
Maturity, %	89.6 (1.90) [b]	89.3 (1.73) [b]	82.8 (1.61) [a]	0.009
Milk yield, L/d	39.7 (1.72) [a]	49.6 (1.41) [b]	53.4 (1.34) [b]	<0.001
Energy-corrected				
Milk, kg/d	41.3 (1.44) [a]	49.5 (1.18) [b]	53.4 (1.12) [b]	<0.001
Fat, g/kg	41.2 (1.39)	38.3 (0.90)	38.4 (0.98)	NS
Protein, g/kg	32.7 (0.67)	33.1 (0.43)	31.3 (00.47)	NS
Live-weight nadir, days in milk	15 (1.6) [ab]	13 (1.5) [a]	20 (1.3) [b]	<0.001
Daily live-weight gain, kg/d	0.52 (0.073) [b]	0.17 (0.067) [a]	-0.04 (0.062) [a]	<0.001
Net live-weight gain, kg	59 (1.4) [a]	31 (1.3) [b]	11 (1.2) [c]	<0.001
Live weight, kg	657 (16.1) [a]	781 (14.7) [b]	773 (13.6) [b]	<0.001
Body condition score	2.95 (0.139)	3.17 (0.119)	2.76 (0.111)	NS

[abc] Statistical significance (p<0.05) is reported with different letters

Table 7.5: Mean (standard error) of milk yield, live weight, and live-weight change adjusted for calving live weight in first nineteen weeks of lactation, according to parity

	Parity			P
	1	2	≥3	
No. of cows	15	18	21	
Milk yield, L/d	39.2 (2.09)	49.1 (1.43)	50.9 (1.47)	NS
Live-weight nadir, days in milk	21 (9.4) [c]	11 (6.4) [a]	16 (6.6) [b]	<0.001
Daily live-weight gain, kg/d	0.25 (0.29)	-0.25 (0.20)	-0.30 (0.20)	NS
Net live-weight gain, kg	53 (8.4) [b]	33 (5.8) [b]	13 (5.9) [a]	<0.001

[abc] Statistical significance (p<0.05) is reported with different letters

Parity 1 cows had lower energy-corrected milk yield than Parity 2 and ≥3 cows (Table 7.4), but there was no difference in milk fat and protein. Parity 1 cows had lower milk yield than Parity 2 and ≥3 cows throughout the study (Figure 7.8a). Peak milk yield was reached in week 8 for cows in Parity 1, and week 7 for cows in Parities 2 and ≥3; peak milk yield was 40.1 L/d for cows in Parity 1, 51.5 L/d for cows in Parity 2, and 56.4 L/d for cows in Parity ≥3. When adjusted for calving LW, only daily milk yield and mean LW gain were significant (Table 7.5).

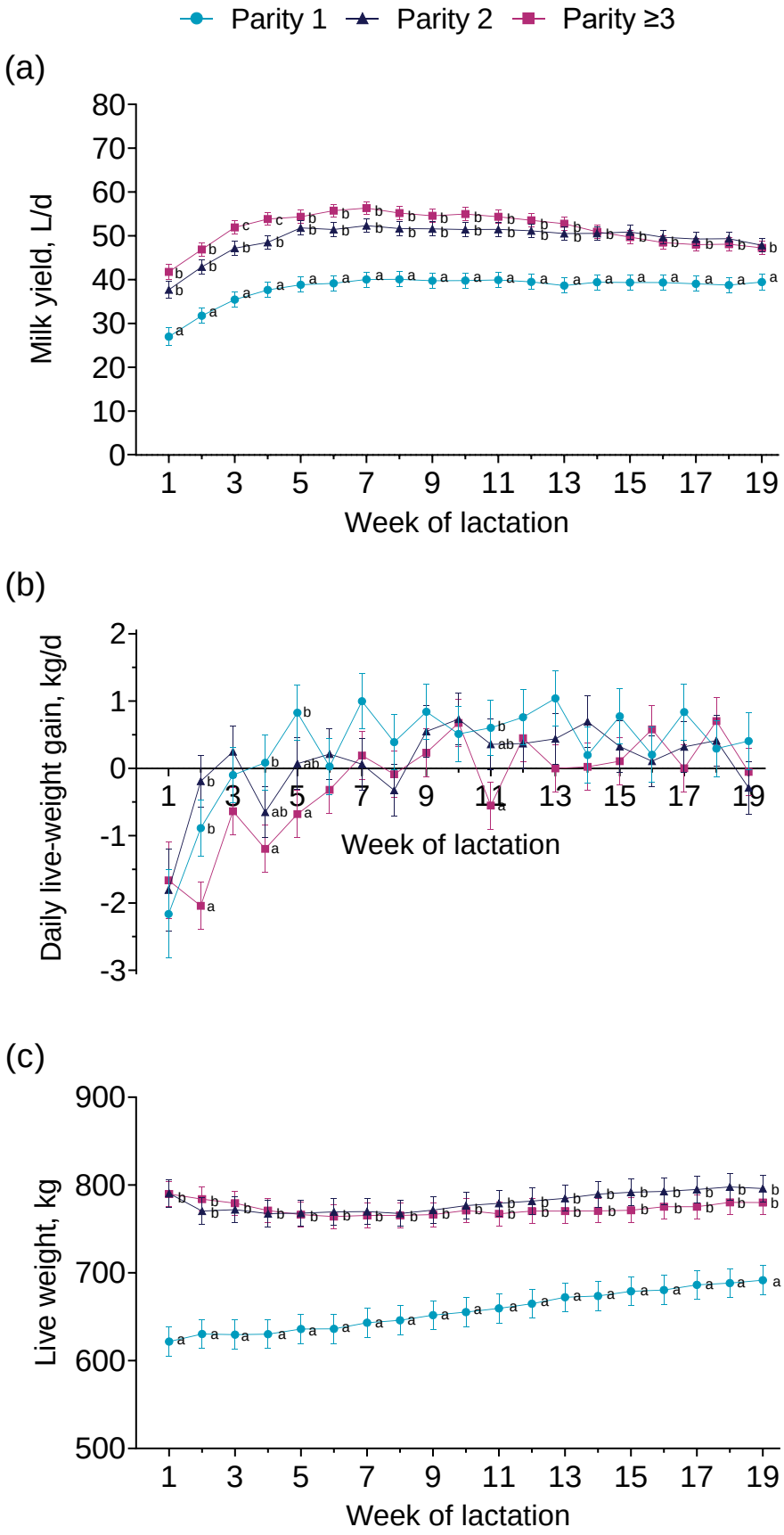


Figure 7.8: Mean (standard error) daily milk yield (a), daily live-weight gain (b) and live weight (c) in first nineteen weeks of lactation, according to parity. **abc** Statistical significance (p<0.05) is reported with different letters

Cows in Parity 2 reached their lowest LW first, followed by Parity 1 cows and Parity ≥3 cows (Table 7.4). However, when adjusted for calving LW, parities were different with Parity 2 cows regaining LW first, followed by Parity 3 cows and lastly Parity 1 cows (Table 7.5). Cows in Parity 1 had higher daily LW gain than Parity 2 and ≥3 cows, with cows in Parity ≥3 having a negative daily LW gain overall (Table 7.4) and the lowest daily LW gain for some WOL (Figure 7.8b). However, when adjusted for calving LW, overall daily LW gain was not different (Table 7.5). Net LW gain was negatively associated with increased parity (Table 7.4), however when adjusted for calving LW, there was no difference between Parity 1 and Parity 2 cows (Table 7.5).

7.3.4 Live weight at first calving

A subgroup analysis of 15 Parity 1 cows on the current study (n=15) was conducted to compare behaviour and performance according to LWFC. LW and maturity at first calving was positively associated with first calving age (Table 7.6).

Table 7.6: Means (standard error) of feed intake, feed behaviour, and performance parameters of first parity cows in first nineteen weeks of lactation, according to live weight at first calving

	Live weight at first calving, kg			P
	≤605	605 to 665	≥665	
No. of cows	5	5	5	
First calving				
Age, days	718 (30.0) [a]	731 (19.6) [a]	782 (23.2) [b]	<0.001
Live weight, kg	587 (13.3) [b]	624 (8.7) [b]	702 (10.3) [a]	<0.001
Maturity, %	82.0 (1.87) [a]	86.8 (1.22) [a]	98.1 (1.45) [b]	<0.001
Dry matter intake, kg/d				
Partial mixed ration	11.7 (0.71) [a]	13.9 (0.46) [b]	14.9 (0.55) [b]	0.010
Robot concentrate	5.9 (0.46)	6.2 (0.30)	6.3 (0.35)	NS
Total	17.7 (0.99) [a]	20.1 (0.65) [ab]	21.2 (0.77) [b]	0.035
% Live weight	2.9 (0.14)	3.1 (0.09)	3.0 (0.11)	NS
Energy requirement, ME MJ/d	257 (20.2)	271 (13.2)	274 (15.6)	NS
ME intake, % ME requirement	86.1 (5.06)	92.1 (3.31)	97.2 (3.92)	NS
Feeding behaviour				
Meal frequency, no./d	7.6 (0.59)	7.2 (0.39)	7.5 (0.46)	NS
Meal duration, min	21.0 (2.87)	24.8 (1.88)	24.2 (2.22)	NS
Meal size, kg DM	1.6 (0.20)	2.1 (0.13)	2.1 (0.15)	NS
Feeding rate, kg/min	0.18 (0.02)	0.19 (0.01)	0.20 (0.01)	NS
Meal timing, %				
0730 to 1030 hrs	18.0 (1.45) [a]	25.9 (0.10) [b]	23.4 (1.12) [b]	0.005
1030 to 1930 hrs	45.6 (2.84)	48.1 (1.86)	46.1 (2.20)	NS
1930 to 0730 hrs	36.4 (3.54)	26.0 (2.32)	30.5 (2.74)	NS

Time budget				
Feeding duration, min/d	151 (15.6)	168 (10.2)	174 (12.1)	NS
Rumination, min/d	444 (11.3)	457 (7.4)	460 (78.8)	NS
Activity, index	40.1 (4.08)	52.6 (2.67)	51.3 (3.16)	NS
Milking frequency, no./d	2.7 (0.29)	2.6 (0.19)	3.0 (0.23)	NS
Milk yield, L/d	34.9 (3.18) [a]	38.1 (2.08) [b]	39.9 (2.46) [b]	<0.001
Live-weight nadir, DIM	0 (18.6) [a]	6 (12.2) [a]	36 (14.4) [b]	<0.001
Mean live-weight gain, kg/d	0.56 (0.30)	0.45 (0.19)	0.05 (0.23)	NS
Net live-weight gain, kg	64 (15.9) [b]	62 (10.4) [b]	50 (12.3) [a]	<0.001
Live weight, kg	611 (22.4) [a]	639 (14.7) [a]	708 (17.4) [b]	0.010

[abc] Statistical significance (p<0.05) is reported with different letters

7.3.4.1 Dry matter intake

Total DMI increased with increased LWFC (Table 7.6). This was mainly because there was a greater difference in PMR DMI between heavier calving cows and lighter calving cows for most WOL (Figure 7.9a). Robot concentrate DMI was not different overall (Table 7.6), but was lower in lighter calving cows than heavier calving cows between weeks 17 and 19 (Figure 7.9b). Overall DMI as a proportion of LW was not affected by LWFC (Table 7.6), however the lightest calving cows consumed a greater proportion than heavier calving cows in week 1 and then a lower proportion than heavier calving cows between weeks 14 and 19 (Figure 7.9d).

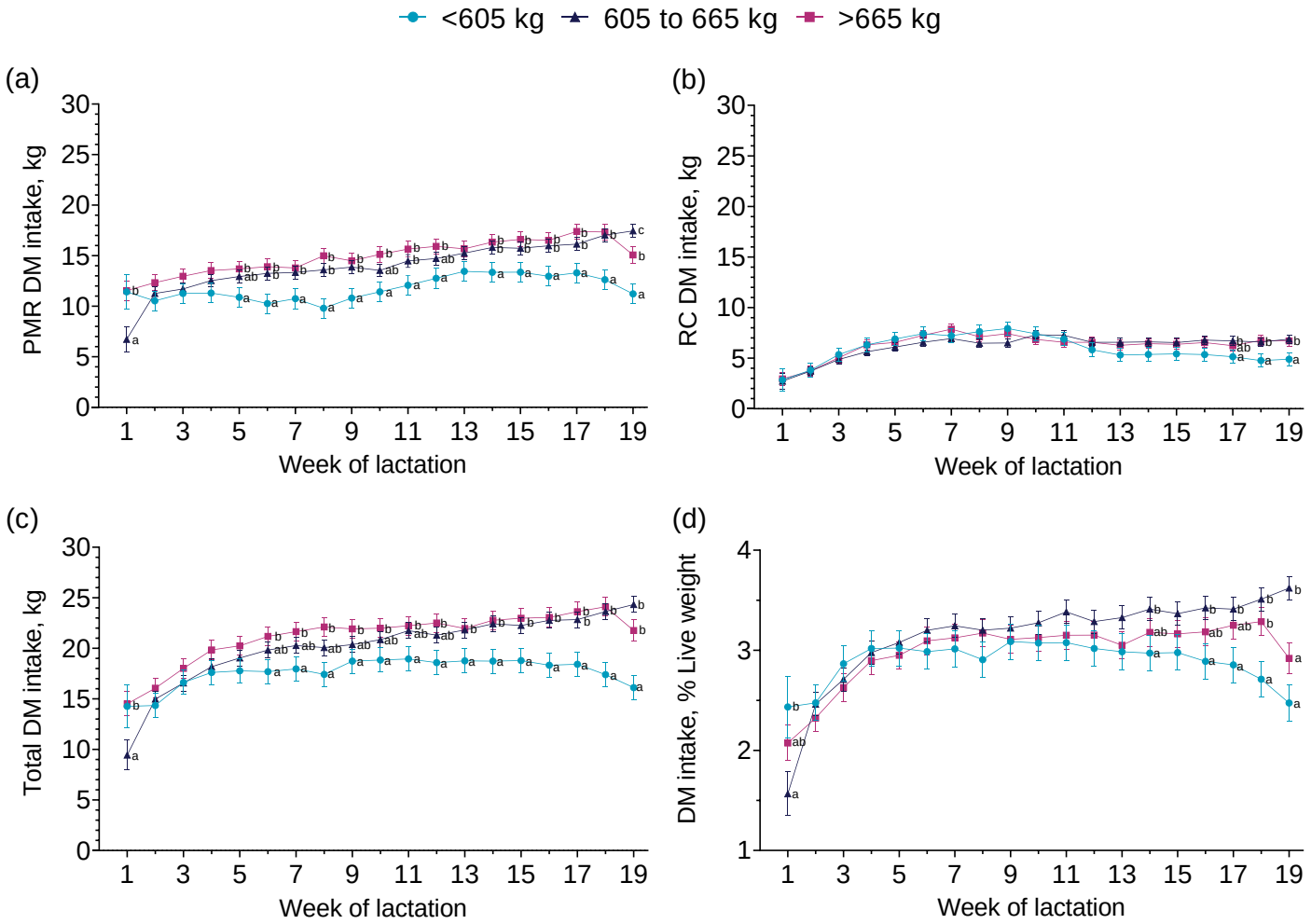


Figure 7.9: Mean (standard error) dry matter (DM) intake of (a) partial mixed ration (PMR), (b) robot concentrate (RC) and (c) total DM intake, and (d) DM intake as a proportion of live weight, in first nineteen weeks of lactation, according to liveweight at first calving
abc Statistical significance (p<0.05) is reported with different letters

ME requirement and ME intake as a proportion of ME requirement was not different between Parity 1 cows of differing LWFC (Table 7.6). Generally, ME intake as a proportion of ME requirement increased with WOL, with lighter calving cows consuming a greater proportion of requirement than heavier calving cows in weeks 18 and 19 (Figure 7.10b).

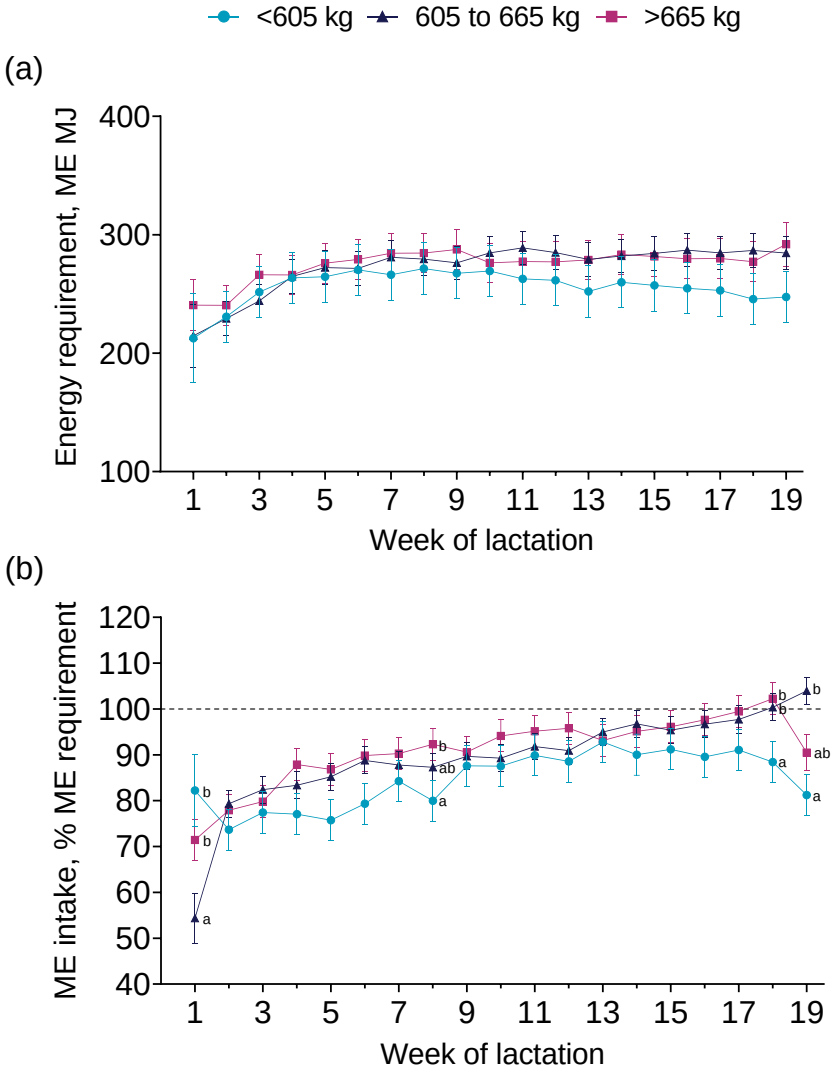


Figure 7.10: Mean (standard error) metabolisable energy (ME) requirement (a) and ME intake as a proportion of ME requirement (b) of first parity cows in first nineteen weeks of lactation, according to live weight at first calving
[abc] Statistical significance (p<0.05) is reported with different letters

7.3.4.2 Behaviour

No feeding behaviour was affected by LWFC (Table 7.6), however, lightest calving cows consumed smaller meals than heavier cows for some WOL (Figure 7.11c).

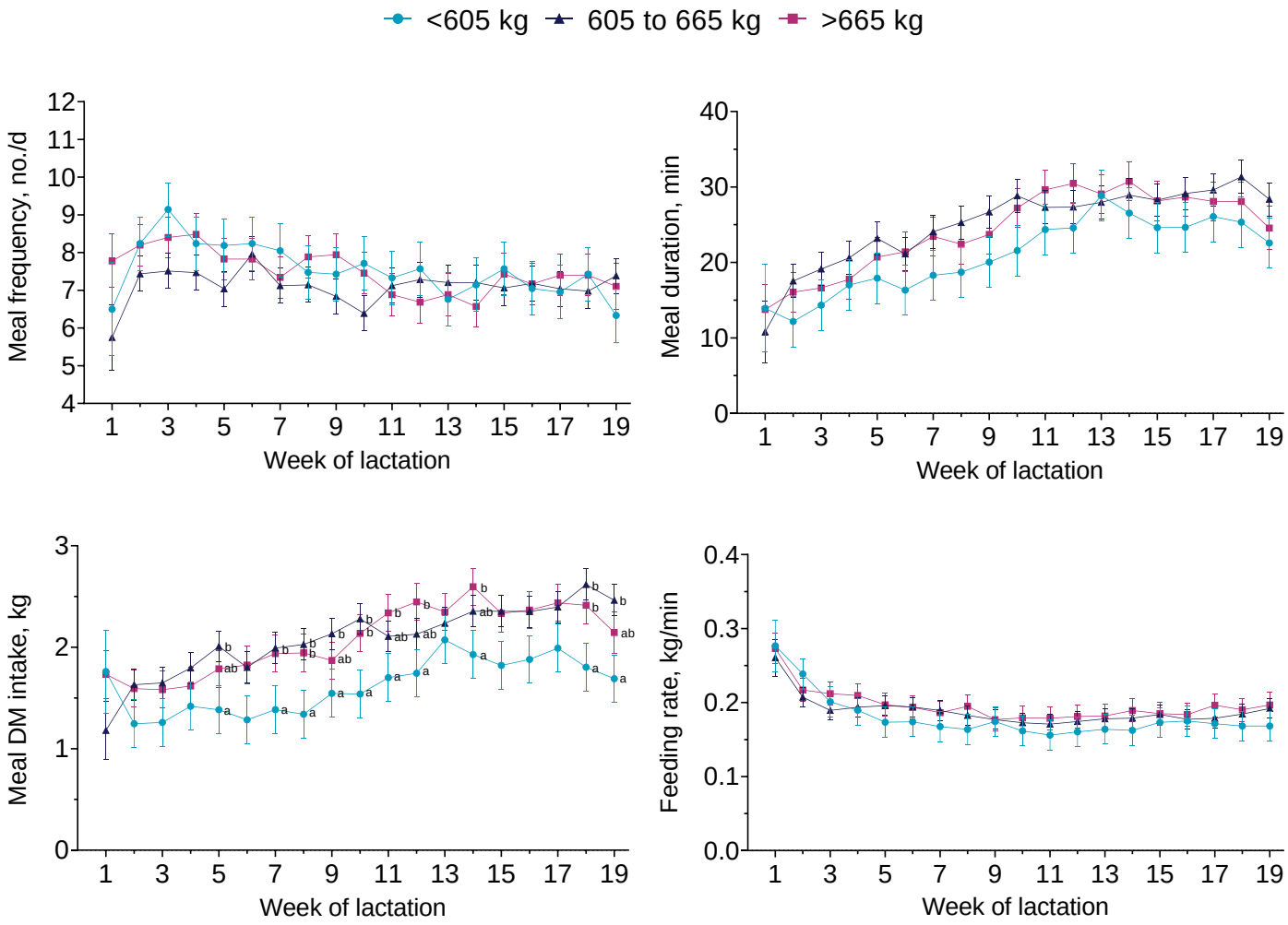


Figure 7.11: Mean (standard error) feeding behaviours; (a) meal frequency, (b) meal duration, (c) meal dry matter (DM) intake and (d) feeding rate of first parity cows in first nineteen weeks of lactation, according to live weight at first calving.
abc Statistical significance (p<0.05) is reported with different letters

Meal timing

Overall proportion of PMR intake consumed during feed delivery was associated with LWFC, however, proportion consumed in the day time and nightime was not (Table 7.6). For some WOL, cows with lightest LWFC consumed a lower proportion of PMR than heavier cows during feed delivery (Figure 7.12a), but ate a higher proportion of PMR than heavier cows during night-time (Figure 7.12c).

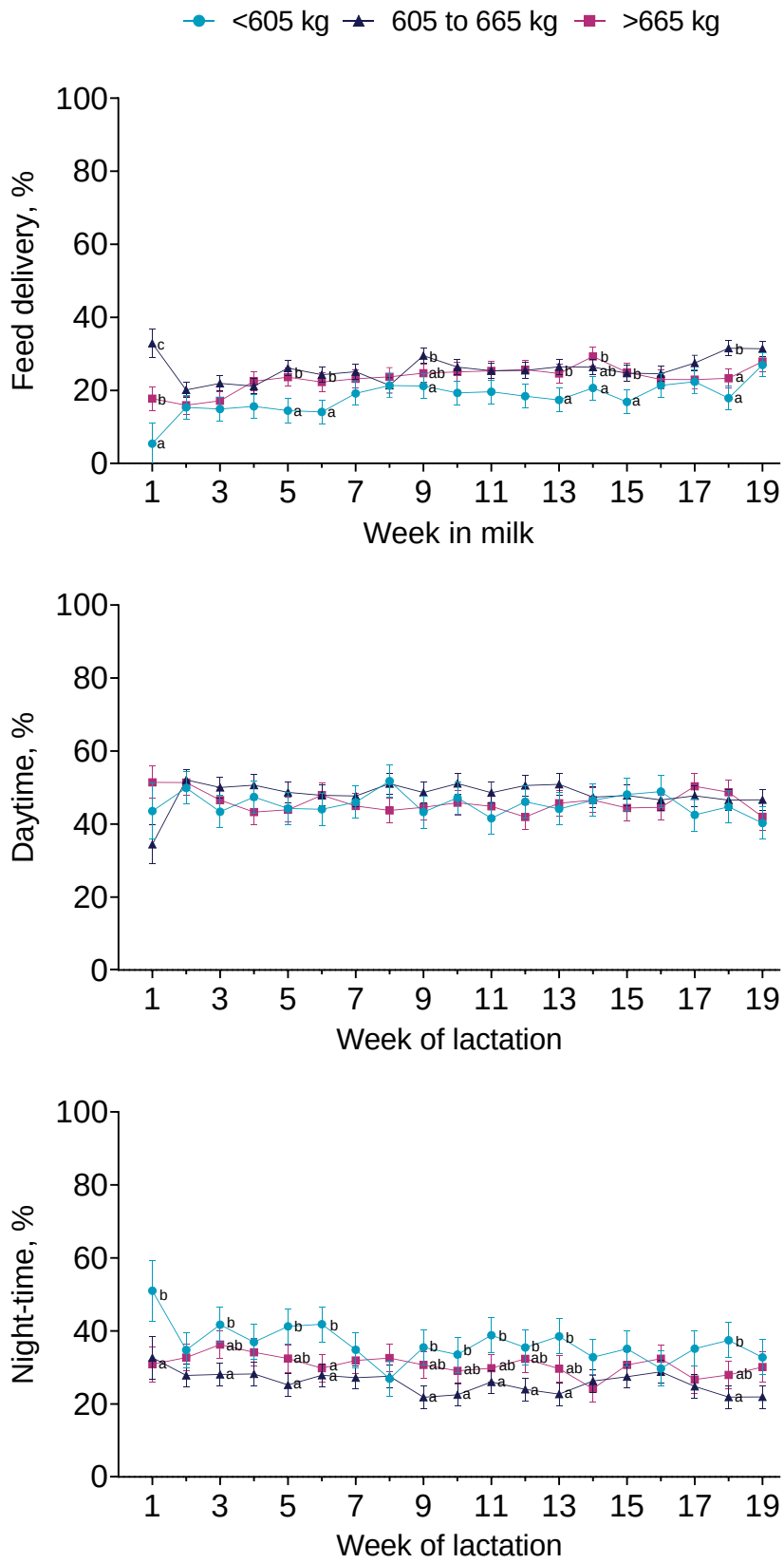


Figure 7.12: Mean (standard error) proportion of partial mixed ration consumed during (a) feed delivery (0730 to 1030 hrs), (b) daytime (1030 to 1930 hrs) and (c) night-time (1930 to 0730 hrs) of first parity cows in first nineteen weeks of lactation, according to live weight at first calving.
abc Statistical significance (p<0.05) is reported with different letters

Daily time budget

Mean feeding duration and rumination were not different between Parity 1 cows of different LWFC (Table 7.6). Generally feeding duration increased throughout the study and lightest calving cows ate for less time than heavier calving cows in weeks 9 and 19 (Figure 7.13a). Lightest calving cows ruminated more than heavier cows in week 1 (Figure 7.13b).

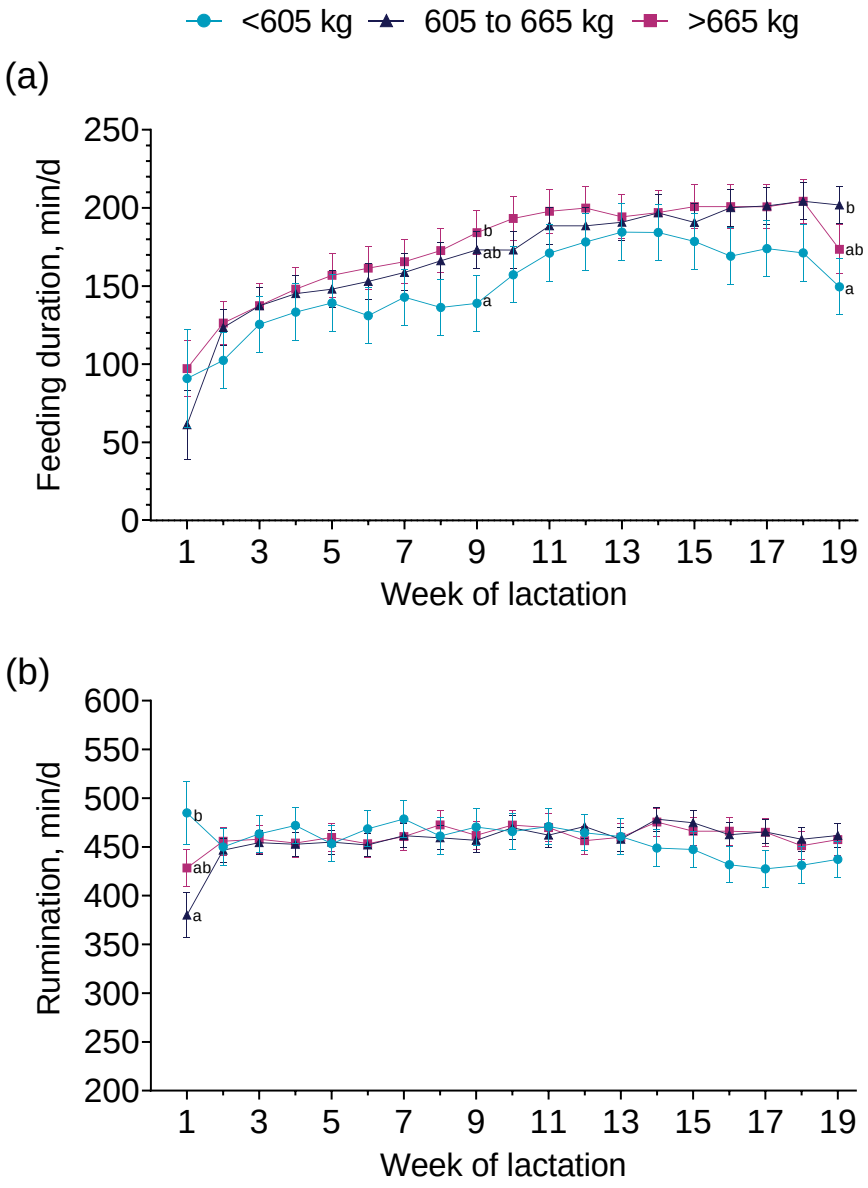


Figure 7.13: Mean (standard error) feeding duration (a) and rumination (b of first parity cows in first nineteen weeks of lactation, according to live weight at first calving. **abc** Statistical significance (p<0.05) is reported with different letters

Mean activity index and milking frequency were not different between Parity 1 cows with different LWFC (Table 7.6). However, lightest calving cows were less active than heavier calving cows in week 3 and between weeks 7 and 19 (Figure 7.14a).

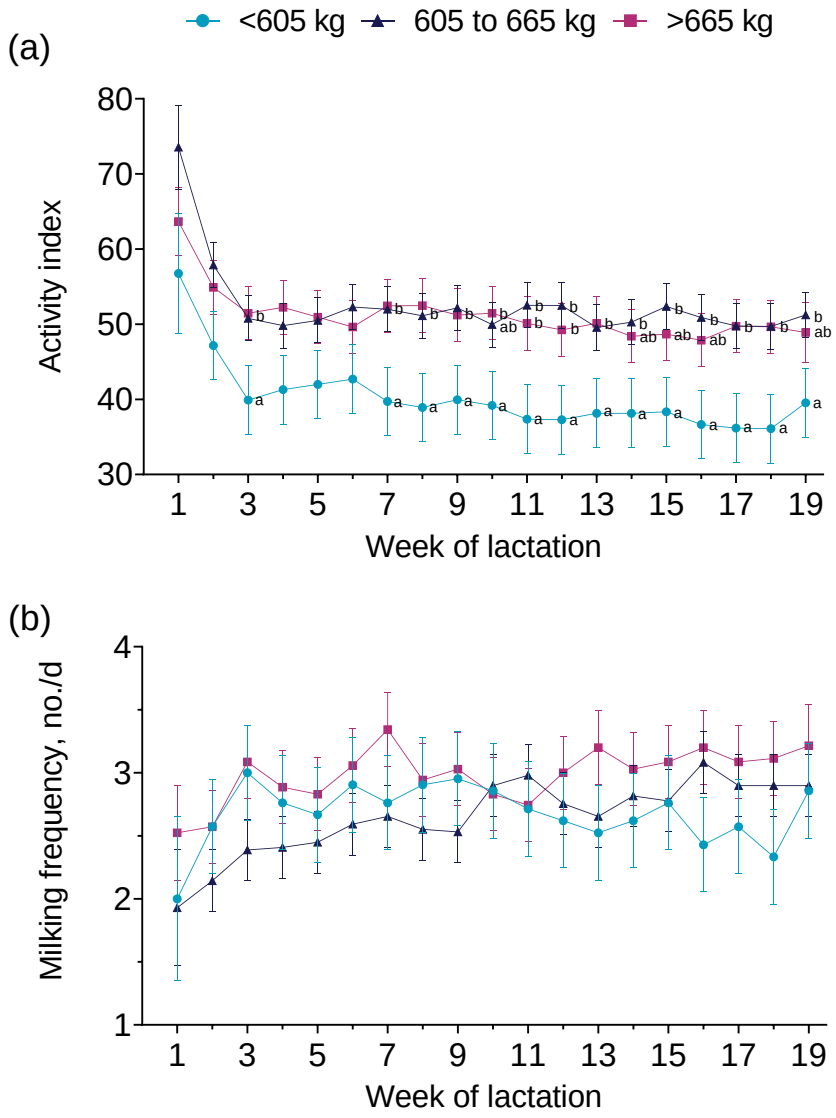


Figure 7.14: Mean (standard error) activity (a) and milking frequency (b) of first parity cows in in first nineteen weeks of lactation, according to live weight at first calving. **abc** Statistical significance (p<0.05) is reported with different letters

7.3.4.3 Milk yield and live weight

There was no difference in mean milk yield (Table 7.6) or between WOL for Parity 1 cows with differing LWFC (Figure 7.15a). Net LW gain was negatively

associated with increased LWFC and there was no effect of LWFC on daily LW gain (Table 7.6). Whereas LW nadir and mean LW were positively associated with increased LWFC (Table 7.6), with the heaviest calving Parity 1 cows achieving a greater LW than lighter calving Parity 1 cows for all WOL (Figure 7.15b).

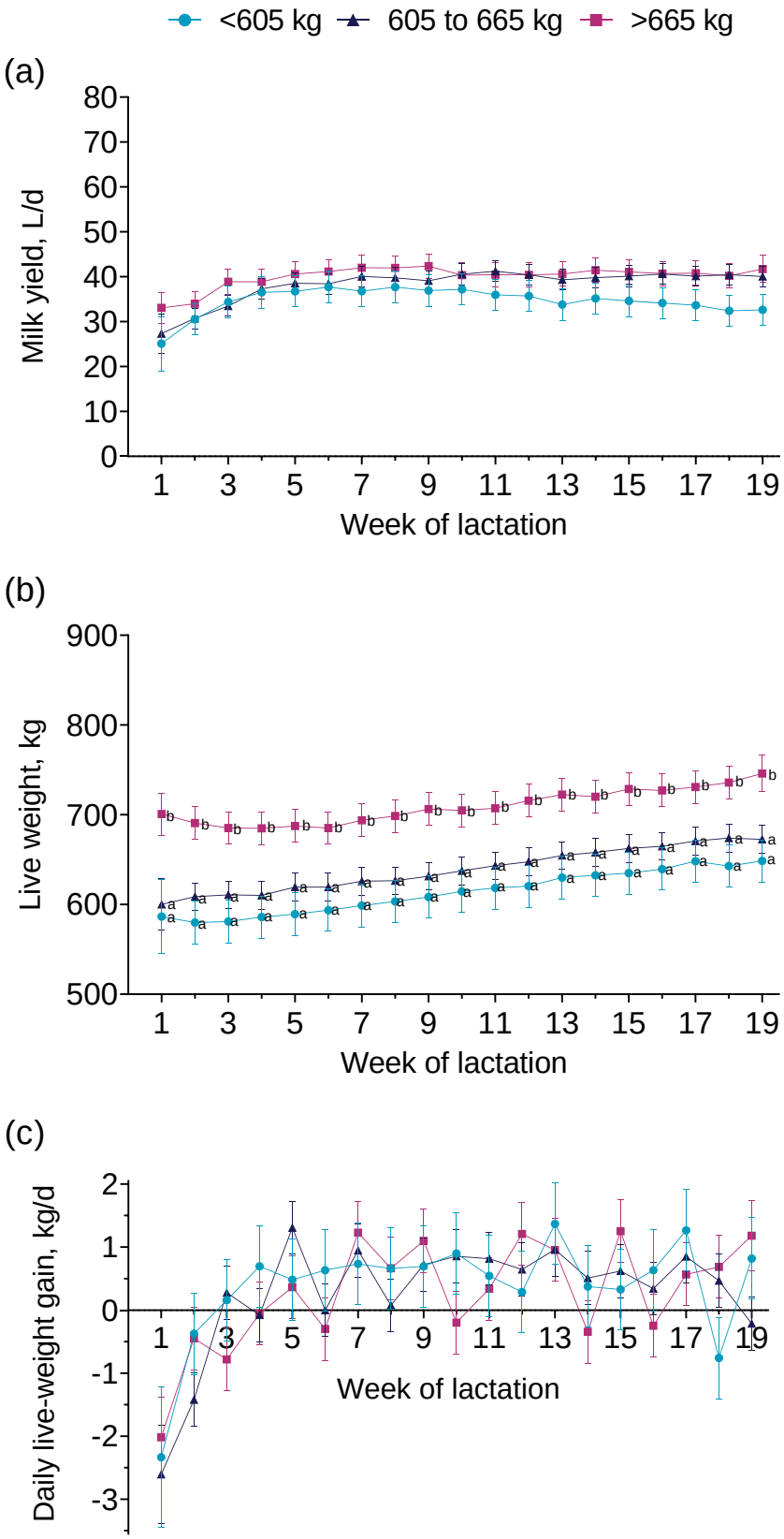


Figure 7.15: Mean (standard error) daily milk yield (a), live weight (b) and live-weight gain (c) of first parity cows in first nineteen weeks of lactation, according to live weight at first calving.
[abc] Statistical significance (p<0.05) is reported with different letters

7.4 Discussion

This study evaluated how Parity 1 cows performed when they first entered the milking herd compared to Parity 2 and ≥3 cows. Specifically, how LW may affect feed intake and behaviour of cows in their first nineteen WOL.

7.4.1 Feed intake

In this study, DMI of Parity 2 and ≥3 cows were 25% greater than Parity 1 cows, which is a similar increase to Azizi *et al.* (2009) who observed that multiparous cows had 22% greater DMI than primiparous cows. In the current study, DMI increased at a similar rate for all Parities over the study period, but differences in PMR DMI contributed to the greater difference in overall DMI between Parity 1 and Parity 2 and ≥3 cows. This result is not surprising as older cows are more likely to be heavier and yield more milk which drives greater DMI. For a similar reason, it was expected that cows with higher LWFC consumed over 10% more DM than the lightest calving cows.

Robot concentrate DMI was different between parities, but not when adjusted for calving LW or between first lactation cows with different LWFC. The Lely system allowed cows to consume robot concentrates *ad libitum* up to a specified daily allowance as described in 0 Abbreviations: ME: metabolisable energy; MJ: megajoule; DM: dry matter

Cow housing and nutrition from 2018 onwards. Thus, a cow with a maximum allowance of 12 kg/d after 70 DIM would have to milk four times a day to receive her full allowance as robot concentrate was restricted to 3 kg per visit. Since cows visited on average 2.9 times per day, robot concentrate intake was generally lower than the full allowance calculated from DIM or milk yield. It was thought that differences in robot concentrate intake might be explained by differences in milking visits between parities. However, there was no difference in overall number of milking visits, and only in the first two WOL did Parity 1 cows visit the AMS less frequently than Parity 2 and ≥3 cows, which is before concentrate allowance was offered individually. Additionally, milking visits were not affected by LWFC in the first nineteen WOL. Therefore, differences in concentrate intake were thought to be because concentrate allowance is primarily influenced by milk yield and DIM, rather than LW.

Parity 1 cows had lower energy requirements and DMI in proportion to their LW compared to Parity 2 and ≥3 cows. This was expected as energy requirements and intake are associated with LW and milk yield, although no difference in ME intake or requirement was observed between Parity 1 cows with different LWFC. Dairy cows are expected to have a DMI between 3 and 4% of their LW, with heavier cows that produce higher yields consuming a greater proportion (Wheeler, 1990). However, the difference in energy intake in proportion to energy requirement was not significant and on average cows ate 97.5% of their requirement. This value was expected as the FiM equations used for ME calculations were published in 2004 using cows from the 1970s to 1990s. Modern cows are heavier and more productive, so are likely to be more efficient and consume less than they apparently require. Additionally, FiM ME requirements are calculated for the 'average' cow, and the prediction error is greater than the discrepancy observed in this study.

It is important to feed to requirement to prevent unnecessary decreases in feed efficiency. It has been shown that excess energy intake in less efficient cows does not result in greater yields or LW but is wasted as heat production and energy loss (Ben Meir *et al.*, 2018). The most efficient cows will use a lower proportion of feed for maintenance, which increases energy allocated for milk production, thus increasing milk production per feed unit, and diluting methane emissions associated with maintenance requirements (VandeHaar *et al.*, 2016). LWFC did not affect ME requirement however, Parity 1 cows were least efficient as a greater proportion of energy was required for growth. Therefore, these cows must enter the milking herd sufficiently developed, so that they reach full maturity as soon as possible to increase the energy allocation for milk production and improve feed efficiency.

7.4.2 Behaviour

It was predicted that Parity 1 cows might consume more meals than older cows due to displacement from feed bins. However, daily meal frequency was lowest in Parity 1 cows (7.2 meals/d) and ≥3 cows (7.3 meals/d), with Parity 2 cows consuming the most meals (7.9 meals/d), although all within previously reported averages between 5.8 (Tolkamp *et al.*, 2000) and 8.7 (Azizi *et al.*, 2009).

Nevertheless, Parity ≥3 cows were able to obtain greater DMI than Parity 1 cows by compensating lower meal frequency with longer and larger meals. Moreover, meal frequency was not different between cows with different LWFC, suggesting other factors beyond age and LW could influence meal behaviour, particularly in high-yielding cows in an AMS.

More frequent and shorter meals are associated with higher digestibility, which is a key factor in improving feed efficiency (Robinson and Oddy, 2004; Llonch *et al.*, 2018), as well as better rumen health (King *et al.*, 2016b). However, Robinson and Oddy (2004), and Llonch *et al.* (2018), used beef cattle and different meal criteria. Robinson and Oddy (2004) defined a meal as a feeding visit where a second visit by the same animal within 2 min of the end of the previous feeding visit was considered as part of the previous session, and Llonch *et al.* (2018) defined a meal as a feeding visit that was refined by eliminating visits in which no feed was consumed and those shorter than 1 minute in duration. This equated to greater meal frequency and shorter meal duration, which are not comparable to cows in the current study.

Overall meal duration was not affected by parity or LWFC and on average cows ate a meal in 27 min. However, between weeks 3 and 10 of lactation, Parity 1 cows did consume shorter meals compared to Parity 2 and ≥3 cows, which could suggest displacement by older cows. Cows would enter the shed randomly according to calving date, therefore, cows were regrouped and re-establishing the social hierarchy constantly. Although not different, meal duration was lowest for all parities in the first two WOL, suggesting that perhaps most cows experience social readjustment when they are introduced to a new group. A two week delay supports previous studies that have shown it can take between 3 days (Kondo and Hurnik, 1990; Grant and Albright, 2001) and 15 days (Bøe and Færevik, 2003; Patison *et al.*, 2010) for social behaviour to return to baseline levels. However, most of these studies used smaller groups of between 12 and 16 animals. All meals in the current study were shorter than those observed by Ben Muir *et al.* (2018) and Azizi *et al.* (2009) who found meal duration ranged between 35 and 38 min. Both studies used high-yielding cows with automated feed bins, but with longer meal criteria intervals (29 min), which

may explain higher meal durations. Similarly, because meal duration was longer, meal size was greater in these two studies (between 2.2 to 4.6 kg DM). In the current study, despite younger and lighter cows consuming smaller meals than older and heavier cows for most WOL, overall meal size was not different and averaged 2.4 kg DM. However, because Parity 1 cows had lower milk yield, therefore lower energy requirement and consume less DM, they could be expected to have fewer and smaller meals.

Overall feeding rate was not affected by parity number or LWFC, with cows on average feeding at a rate of 0.21 kg DM /min. This was at the higher end of reported rates, which are between 0.07 kg/min (Azizi *et al.*, 2009) and 0.26 kg/min (Krpálková *et al.*, 2021). Faster feeding rate has been identified as a potential indicator of poor rumen health because a fast feeding rate reduces saliva production, increases rumen passage, and reduces digestibility (King *et al.*, 2016b; Krpálková *et al.*, 2021). Due to increasing acidity of the rumen, cows that ate faster were at greater risk of metabolic problems, such as acidosis, but also had reduced digestibility and feed efficiency. Furthermore, cows that are obliged to spend less time feeding often compensate the time debit by eating faster. However, Parity 1 cows consistently ate slowest throughout the current study and only from week 10 of lactation did Parity 2 and ≥3 cows begin eating faster than Parity 1 cows. Older cows have been found to eat faster to facilitate higher DMI needed to support greater milk yield (Grant and Albright, 1995), although, Krpalkova *et al.* (2021) found that cows eating less than 0.14 kg DM/min had greater DMI, milk yield, LW, feed conversion ratio and resting duration. Additionally, physical characteristics of the diet may have influenced feeding rate. All forages had short chop length and high DM, which are known to encourage fast eating (Addah *et al.*, 2015) and reduce sorting (Leonardi and Armentano, 2003; Havekes *et al.*, 2020). Therefore, reviewing management practices and feed factors that might increase feeding time and reduce feeding rate of Parity 1 cows would be useful for attaining these benefits.

There was no effect of parity number on timing of PMR intake, with cows on average eating 25% of their PMR intake at feed delivery (0730 to 1030 hrs), 47% during daytime (1030 to 1930 hrs) and 29% during night-time (1930 to

0730 hrs). This result is similar to Dürst *et al.* (1993) who reported that 89% of meals were consumed during the light phase of the day (0400 to 2200 hrs) and Rottman *et al.* (2014) who suggested that 30% of overall daily intake is consumed between 1200 and 1800 hrs. This could be because cows naturally tend to rest and ruminate during night hours and graze in early morning and late afternoon when nutrients are more available in pasture (Gregorini, 2012; Schirmann *et al.*, 2012; Sheahan *et al.*, 2013). However, there were differences between parities during feed delivery in the first four WOL. Although Parity ≥3 cows consumed less PMR DM than younger cows in week 1 of lactation, they consumed more PMR DM than younger cows between weeks 2 and 4. Results in week 1 could be due to adjustment to the feed system and social hierarchy as described earlier, before establishing dominance over younger cows. Additionally, there were differences due to LWFC, with the lightest first calving cows eating over 24% less of their total PMR DMI during feed delivery compared to heavier first calving cows. As a result, for some WOL lighter calving cows consumed more PMR DM during the night compared to heavier calving cows. This supports previous studies that found the most acute differences in DMI and feeding duration occur during feed delivery (von Keyserlingk *et al.*, 2008; Neave *et al.*, 2017).

Although competition for feed is inevitable, dominance has a greater effect at higher stocking densities and when feeding space and availability are limited (Longenbach *et al.*, 1999; Huzzey *et al.*, 2006). In the current study, stocking density was 14.1 m^2/cow, which is well in excess of average housed systems of 8.3 m^2/cow (Thompson *et al.*, 2020). Additionally, the quantity of fresh feed was calculated daily to ensure it was offered at 110% of expected intake. Greater access to truly *ad-libitum* feeding may have reduced competition during feed delivery allowing Parity 1 cows to feed. However, feeding space was limited to 1.6 cows per feed bin, therefore at peak feeding times some cows may be waiting to access a free feed bin. Feeding space and design are critical factors of social competition and need to be considered when improving DMI in Parity 1 cows and overall feed efficiency.

Lack of significance in meal timing may be because the time intervals in the current study were too long to distinguish small effects on timing of intake. In CMS, Ben Muir *et al.* (2018) found intake was associated with external events, with five distinct peaks after each milking (three times daily; 0500, 1300 and 2100 hrs), feed delivery (0900 hrs) and between the second and third milking. However, the circadian pattern of diurnal distribution and synchronicity between parity was not analysed in the current study and this information would be useful to compare circadian patterns in high-yielding cows in AMS.

Some studies have shown that housing Parity 1 cows separately can improve DMI by 12%, feeding time by 11%, and lying time by 9% and increase milk yield by 5% (Krohn and Konggaard, 1979). Furthermore, a uniform group of cows allows for more accurate ration formulation, especially as heifers also have greater growth requirements, which decreases nutrient excretion and reduces environmental impact (St-Pierre and Thraen, 1999). Depending on farm size and management practices, separate housing and/or diet ration for Parity 1 cows could be an option for some dairy systems. Results of the current study suggest, however, that separate housing for Parity 1 cows might have no benefit when cows have a generous space allowance.

Overall daily feeding duration was not affected by parity number or LWFC, with cows on average feeding for 188 min/d, which was lower than in other studies which ranged from 208 min/d (Ben Meir *et al.*, 2018) to 312 min/d (Krpálková *et al.*, 2021). In the current study, feeding duration was shorter in Parity 1 cows between weeks 1 and 10 of lactation compared to Parity 2 and ≥3 cows. It was expected that daily feeding duration would increase to support increasing milk yield, as shown in previous studies (Gomez and Cook, 2010; Johnston and DeVries, 2018), although Azizi *et al.* (2009) found that there was no effect of milk yield on feeding behaviour. Shorter feeding duration has also been associated with competition for feed (Llonch *et al.*, 2018), for reasons as previously described. So, perhaps, the effect in weeks 1 to 10 was associated with feed competition, and by week 10 Parity 1 cows were able to stabilise themselves in the social order and were displaced at feed bins less frequently, therefore were able to feed for longer.

Overall daily rumination was not affected by parity number or LWFC, with cows on average ruminating for 574 min/d, which is similar to reported averages ranging between 427 min/d (Ben Meir *et al.*, 2018) and 608 min/d (Krpálková *et al.*, 2021). However, Parity 1 cows did ruminate for less time than Parity 2 and ≥3 cows between weeks 1 and 7 of lactation, which supports some studies that suggest parity number affects rumination activity (Dado and Allen, 1994; Miedema and DeVries, 2016; Stone *et al.*, 2017). Additionally, LWFC affected rumination in the first WOL and last two WOL. Rumination was positively related to milk yield (Soriani *et al.*, 2012; Stone *et al.*, 2017) and has been associated with lying time and cow health (Hansen *et al.*, 2003; Radostits *et al.*, 2006). Lying is crucial for milk synthesis due to increased blood flow through the udder and it has been proposed that one additional hour of lying can increase milk yield by 0.9 to 1.6 kg/d (Grant, 2004). It has been found that cows prioritise lying over feeding (Munksgaard *et al.*, 2005), so this may contribute to lower DMI if Parity 1 cows are unable to lie for sufficient time. However, a benefit of AMS is that eliminates holding time in a collecting yard and milking parlour, which is a feature of CMS that would reduce lying and feeding time.

Overall activity index was not affected by parity number or LWFC and was 47.8 for an average two-hour period. Studies have reported activity index using QWES tags as a 24 hr average between 339 (King *et al.*, 2017) and 719 (Watt *et al.*, 2015), which when calculated as a two-hour period are similar to the current study. Parity 1 cows were more active than Parity 2 and ≥3 cows in weeks 1 and 2 of lactation, and lighter calving cows were less active than heavier calving cows for several WOL. This was unexpected as lighter cows were expected to be displaced more, particularly in the first 15 days after herd introduction (Bøe and Færevik, 2003; Patison *et al.*, 2010), therefore their activity would be higher initially, so time spent on other behaviours, such as ruminating, milking, lying, and feeding, would be lower.

7.4.3 Milk yield and live weight

Parity 1 cows had lower milk yield than Parity 2 and ≥3 cows, which previous studies ascribe to lower DMI and maturity (DePeters *et al.*, 1985; Buckley *et al.*, 2003). However, when adjusted for calving LW, there was no difference

between parities and, unexpectedly, there was no effect of LWFC on first lactation milk yield. Many studies have shown that heifers with greater LWFC achieve higher first lactation milk yield (Hoffman and Funk, 1992; Carson *et al.*, 2002; Macdonald *et al.*, 2005). However, in the current study, there were low numbers of heifers in each LWFC group (n=5), and heifers were heavier at first calving (mean ± SD: 643 ± 62 kg) than heifers in other studies (range: 378 to 635 kg). A small sample of Parity 1 cows is a limitation to LWFC analyses in the current study, and it would be useful to repeat this study with a larger sample of heifers in a high-yielding system to further explore effects of LWFC on behaviour and performance in first lactation.

A dairy cow goes through a variety of stressors when transitioning from gestation to lactation, including separation from a calf, moving to different housing with new herd mates, and diet changes (Mulligan and Doherty, 2008). Parity 1 cows may find this process more stressful than older cows in addition to learning to milk, and so, may milk less frequently. This can be seen in the first two WOL when Parity 1 cows visited the AMS least frequently compared to the rest of the study. Several studies have found a positive correlation between daily milk yield and daily milking frequency (Nixon *et al.*, 2009; DeVries *et al.*, 2011; Løvendahl and Chagunda, 2011; Vijayakumar *et al.*, 2017), and greater stress can put cows at higher risk of not being able to compete within the herd for food (Proudfoot *et al.*, 2014; Jensen and Proudfoot, 2017). An advantage of CMS is that cow behaviour in the parlour can be synchronised through social facilitation (King *et al.*, 2016a), which may be an intrinsic herd behavioural strategy to avoid predation (Cooper *et al.*, 2008), and can also support individual cow learning (King *et al.*, 2016a). However, cows in an AMS have fewer stressors and better welfare as individuals; cows can choose when to milk, allowing subordinate cows to wait until the AMS is empty to avoid confronting dominant cows (Ketelaar-de Lauwere *et al.*, 1996; Hopster *et al.*, 2002). Additionally, cows are not forcibly driven to a milking parlour or withstand long waiting times in a collecting yard. Training Parity 1 cows to use AMS involves fetching individuals which have not milked for 6 to 8 hours. Therefore, strategies to encourage greater voluntary AMS visits in Parity 1 cows may increase their milking frequency and milk yield.

Throughout this study, Parity 1 cows had lower LW than Parity 2 and ≥3 cows. Unsurprisingly, Parity 1 cows with lighter LWFC had lower LW compared to heavier calving cows. Cows do not reach full maturity until approximately 1,400 days of age (Coffey *et al.*, 2006), so Parity 1 cows were still growing, whereas most Parity 2 and ≥3 cows had reached mature weight. Thus, Parity 1 cows had greatest DLWG, however, when adjusted for calving LW, DLWG was not significantly different between parities, nor between Parity 1 cows with different LWFC. Smaller cows require a larger portion of energy intake to support growth, which reduces as they reach a higher proportion of mature weight, leaving more energy for maintenance and production (VandeHaar *et al.*, 2016). Therefore, it is important that heifers calve with sufficient LW so that they reach maturity sooner and can proportion more energy towards milk production.

Mean days from calving to LW nadir increased from cows with lower to higher LWFC and from first to later parities. Likewise, younger, and lighter calving cows had greater net LW gain than older and heavier calving calves. Fewer days between calving and LW nadir, coupled with a lower LW loss from calving to LW nadir and greater post-nadir increase in relative LW indicates a smaller energy deficit in early lactation (van Straten *et al.*, 2008). This is important as cows which experience severe negative energy balance have delayed ovulation (Westwood *et al.*, 2002). Therefore, it is critical that cows successfully transition into the milking herd and quickly adapt to lactation by consuming sufficient DM to support milk yield and control tissue mobilisation.

7.5 Conclusion

This study showed that Parity 1 cows in an AMS have increased activity and reduced feeding duration, rumination, and milking frequency than older parities in the first ten weeks of lactation. These factors may reduce DMI of Parity 1 cows which influences their growth, milk yield, and feed efficiency in the first lactation. Therefore, this study highlights that Parity 1 cows need sufficient time to feed and lie down throughout the day to improve LW gain, milk yield and rumen health. Stocking density, feeding space and design, and feed availability are still important in reducing competition and displacement so that Parity 1

cows can spend longer feeding and resting. However, over 50% of the time budget for the average cow was unaccounted for and further work is recommended to explain remaining daily behaviours. It is critical to encourage greater DMI in first lactation so that cows reach maturity sooner and can allocate more energy to milk production. However, this needs to be supported by growing heifers efficiently so that they calve at the correct LW. There was no difference in behaviour between heifers calving at different LW, but due to small sample size in this study, it is suggested to repeat these results were greater numbers. These results support suggestions that feeding behaviours can reflect health, welfare, and feed efficiency of dairy cows. There is potential for feed behaviours, such as meal frequency and meal duration, to be useful tools in assessing feed efficiency in dairy systems, but further work is required to determine associations in high-yielding dairy cows. Providing an environment where Parity 1 cows can achieve and maintain high DMI will help heifers realise their milk yield potential and return investments made in the rearing period sooner.

Chapter 8

Age at first calving and herd performance

8.1 Introduction

For dairy systems to be profitable, it is essential that heifers are reared for a productive and long herd life (Brickell and Wathes, 2011; Boulton *et al.*, 2017). The heifer rearing period is financially unproductive and its associated costs are the second-largest overhead following feed costs, accounting for 15 to 20% of total expenses (Heinrichs, 1993; Gabler *et al.*, 2000). Boulton *et al.* (2017) found it took on average 530 days from first calving for a heifer to repay her rearing costs (mean estimate of £1819) with poor health, growth and fertility delaying age at first calving (AFC) and further adding to rearing costs.

The association between AFC and longevity has been found to have a direct effect on productivity and profitability. Reducing a 760 days (25 months) AFC by 30 and 122 days, increased the margin between milk return and rearing costs by 4% and 18% per heifer respectively, whereas an AFC of 882 days (29 months) increased rearing costs by 14% without realising a proportionate increase in milk return, so was less profitable (Tozer and Heinrichs, 2001). Additionally, heifers calving after 730 days (24 months) have reduced lifetime performance and survivability to second lactation, thus further reducing profitability (Bach, 2011; Brickell and Wathes, 2011). Calving earlier than 730 days (24 months), however, has been associated with higher risk of dystocia (Hoffman, 1997), lower first lactation milk yield and reduced reproductive performance (Ettema and Santos, 2004), which needs be considered when setting calving targets.

Based on these findings, it is generally accepted that 730 days (24 months) is the optimum AFC to balance lifetime productivity and profitability (Wathes *et al.*, 2014) and is an industry-recognised target in the UK (Cooke *et al.*, 2013). However, 730 days (24 months) is a longstanding recommendation that was first suggested in the 1990s (Hoffman and Funk, 1992; Heinrichs, 1993) and is rarely achieved in many countries, with mean AFC ranging from 745 to 943 days (24.5 to 31 months) (Ojango and Pollott, 2001; Brickell *et al.*, 2009a; Froidmont *et al.*, 2013). In the UK, a recent report showed that mean within-

herd AFC was 821 days (27 months), and this has not changed since 2015 (Hanks and Kossaibati, 2020).

This study aimed to evaluate effects of AFC on first lactation and lifetime performance, in particular the effect of calving heifers before the 730 days (24 months).

8.2 Material and Methods

8.2.1 Animals and location

This was a retrospective study carried out using Holstein-Friesian heifers born at the Nottingham University Dairy Centre between 2007 and 2018. Heifers were selected if they had a recorded date of first calving and a first lactation milk yield greater than 0 (n=883).

8.2.2 Management

All animals were fed and housed as described in 2.2 Youngstock management and 2.3 Adult cow management, and mated as described in 2.4 Heifer and cow reproduction.

8.2.3 Data collection

SQL was used to extract historic data for AFC; live weight (LW); milk yield, days in milk (DIM) and dry-off date per lactation; and culling date. LW was measured using load cells fitted to the automatic milking systems (AMS: Lely Astronaut A3; Lely Ltd., UK) and uploaded to T4C. LW at first calving (LWFC) and at second calving (LWSC) were calculated as mean LW in the first 7 days post-calving. Estimated daily LW gain (DLWG) from birth to calving was calculated by dividing LWFC minus 41 kg (assumed birth weight (Archer, 2021)) by AFC; and from first to second calving was calculated by the difference between LWFC and LWSC, divided by first lactation calving interval. Average herd mature weight (MW) was calculated for each year of birth as mean LW of cows in ≥3 lactations and between 100 and 200 DIM, and used to calculate target 55% and 85% MW.

First lactation data were analysed in 708 heifers that had calved for a second time. First lactation data examined were AFC, LWFC, LWSC, DLWG from first calving to second calving, proportion of LW gained (LW difference between first and second calving divided by LWFC), number of serves, CR, days to second pregnancy (difference between AFC and age at successful service (diagnosed pregnant), first lactation DIM, calving interval, first lactation milk yield, and mortality before 150 DIM and second calving. CR was calculated for individual heifers and defined as reciprocal of number of services, i.e., 1 serve =100%, 2 serves = 50%, 3 serves = 33% etc.

Lifetime performance data were analysed in 679 culled animals. Lifetime performance data examined were lifetime milk yield, lifetime DIM, lifetime daily yield (LDY; lifetime milk yield divided by culling age), days spent unproductive (AFC plus dry days), culling age (days), lactation of culling, breakeven age (days), days in profit, profitable life and productive life. Days in profit was defined as number of days exceeding breakeven age, where breakeven age was calculated as the age at which a heifer returns her rearing costs ((AFC plus 530 days (Boulton *et al.*, 2017)) with negative values adjusted to 0. Profitable life was defined as the proportion of life spent in profit (days in profit divided by culling age) and productive life was defined at the proportion of life spent lactating (lifetime days in milk divided by culling age.

Exit reason was gathered from notes recorded by herd management staff when cows left the herd. Exit reasons were grouped as either died, euthanised or sold, and reasons which were put as unknown or left blank were defined as unspecified.

8.2.4 Statistical analysis

Data were collated using Microsoft Office Excel (2016) and analysed using GenStat (21st edition; VSN International, UK). Data were grouped according to AFC; Early: <700 days (<23 months), Target: 700 to 760 days (23 to 25 months), Late: 760 to 852 days (25 to 28 months) and Very Late: >852 days (>28 months). Data for first lactation and lifetime performance were analysed using Generalized Linear Models with AFC as the fixed effect. Normal error

distribution was used for LW, DLWG and milk yield data; Poisson error distribution with a log-linear link function was used for data comprising days and number of lactations or services. For variables with a dispersion parameter below 1, dispersion parameter was fixed at 1, and for variables with a dispersion parameter above 1, dispersion parameter was estimated. Kaplan-Meier survival analysis was performed to assess the effect of AFC of heifers that had calved for the first time on herd longevity. Rank tests were used to determine short (Wilcoxon) and long-term (log-rank) effects of AFC on herd longevity. The log-rank test places more weight on greater culling ages, and the Wilcoxon test places more weight on early culling because a weighted average of each residual (observed minus expected) deviation is obtained by using the number of survivors in the group at each time. Estimates of survival function were used to create a Kaplan Meier plot in Graphpad Prism (Version 9.3.1, GraphPad Software, CA). Data for cumulative mortality were analysed using chi-square contingency tables with AFC group and lactation of culling as a factor. Statistical significance is reported at $p<0.05$ and differences between treatments were compared using Bonferroni tests with a 95% confidence interval. Non-significant effects are reported as NS. Tabulated means are presented with their standard error and interquartile rage (IQR).

8.3 Results

8.3.1 First lactation performance

From 2007 to 2018, 80.2% of heifers that had calved completed their first lactation and calved for a second time (n=708). Performance of these heifers during first lactation is presented in Table 8.1.

Table 8.1: Descriptive statistics for first lactation parameters of 708 heifers that calved a second time between 2007 and 2018

	Mean	Median	Lower quartile	Upper Quartile	Standard deviation
First calving:					
Age, days	754	749	705	797	77
Live weight, kg	600	601	552	699	70
Maturity, %	87.3	87.2	82.0	92.3	8.5
Second calving					
Live weight, kg	672	669	613	726	79
Live-weight gain, kg/d	0.25	0.24	0.13	0.37	0.18
Live-weight gain, %	14.7	13.7	6.8	21.1	11.4
Number of services	2.6	2.0	1.0	3.0	1.9
Conception rate, %[1]	58	50	33	100	33
Days to successful service (diagnosed pregnancy)	106	86	61	132	65
Days in milk	335	320	295	363	62
Calving interval, days	383	364	339	411	62
Milk yield, L	11,566	11,232	9,573	13,198	3,022

[1]Conception rate was calculated for individual heifers and defined as reciprocal of number of services, i.e., 1 serve =100%, 2 serves = 50%, 3 serves = 33% etc.

Age, LW, and maturity at first calving increased with AFC, and each AFC group was significantly different (Table 8.2). Heifers calving early were the lightest group at first and second calving and had the greatest DLWG in their first lactation, but DLWG was only different compared to very late calving heifers. However, heifers calving early gained a significantly higher proportion of their LWFC compared to older calving groups. Heifers calving on target and late were the only groups to calve with recommended maturity (85 to 90% MW). Despite gaining a similar proportion of LW at a similar rate, however, heifers calving late were significantly heavier at second calving than heifers calving on target. Heifers calving very late exceeded maturity targets and had a significantly lower DLWG than younger calving groups, and gained the smallest proportion of LWFC. There was no difference between groups in number of services, although early calving heifers were in-calf significantly sooner and had a significantly lower calving interval than very late heifers. First lactation milk yield increased with AFC, with very late calving heifers yielding over 1,500 L more than early calving heifers. There was no difference between groups in either mortality before 150 DIM or mortality before second calving.

Table 8.2: Mean (standard error) first lactation performance data in heifers born between 2007 and 2018 (n=708), according to age at first calving; Early: <700 days (<23 months), Target: 700 to 760 days (23 to 25 months), Late: 760 to 852 days (25 to 28 months) and Very Late: >852 days (>28 months)

	Age at first calving				P
	Early	Target	Late	Very Late	
No. animals	162	243	233	70	
First calving:					
Age, days	661 (2.0) [a]	731 (1.7) [b]	978 (1.9) [c]	906 (3.6) [d]	<0.001
Live weight, kg	558 (5.0) [a]	592 (4.1) [b]	618 (4.2) [c]	659 (7.6) [d]	<0.001
Maturity, %	82.5 (0.55) [a]	86.3 (0.44) [b]	89.7 (0.45) [c]	94.2 (0.80) [d]	<0.001
Second calving					
Live weight, kg	618 (7.1) [a]	664 (5.6) [b]	695 (5.5) [c]	720 (9.2) [c]	<0.001
Live-weight gain, kg/d	0.28 (0.019) [b]	0.25 (0.014) [b]	0.26 (0.014) [b]	0.17 (0.023) [a]	0.003
Live-weight gain, %	18.8 (1.10) [b]	14.7 (0.86) [a]	14.1 (0.86) [a]	9.6 (1.42) [a]	<0.001
Number of services	2.3 (0.13)	2.6 (0.11)	2.7 (0.12)	2.6 (0.20)	NS
Conception rate, %[1]	62.0 (2.55)	57.2 (2.10)	55.8 (2.15)	56.6 (3.86)	NS
Days to successful service[2]	95 (4.4) [a]	107 (3.9) [ab]	109 (4.0) [ab]	117 (7.5) [b]	0.034
Days in milk	324 (4.6) [a]	332 (3.8) [b]	341 (3.9) [c]	346 (7.2) [c]	0.014
Calving interval, days	370 (4.8) [a]	384 (4.0) [ab]	387 (4.2) [ab]	394 (7.4) [b]	0.014
Milk yield, L	10,895 (235) [a]	11,394 (192) [ab]	11,957 (196) [b]	12,418 (357) [b]	<0.001
Mortality before					
150 days in milk, %	5.7 (1.67)	4.9 (1.32)	5.5 (1.35)	8.8 (2.42)	NS
Second calving, %	14.1 (2.76)	18.9 (2.18)	18.1 (2.24)	20.9 (4.01)	NS

[1]Conception rate was calculated for individual heifers and defined as reciprocal of number of services, i.e., 1 serve =100%, 2 serves = 50%, 3 serves = 33% etc.

[2] Successful service defined as service resulting in diagnosed pregnancy

[abc] Statistical significance (p<0.05) is reported with different letters

8.3.2 Lifetime performance

From 2007 to 2018, 76.9% of heifers that had calved for the first time were culled (n=679). Performance of these heifers during their lifetime is presented in Table 8.3.

Table 8.3: Descriptive statistics of lifetime performance parameters from 679 culled heifers born between 2007 and 2018

	Mean	Median	Lower quartile	Upper Quartile	Standard deviation
Lifetime days in milk	872	784	416	1,229	551
Lifetime milk yield, L	32,592	29,299	15,409	45,878	22,031
Lifetime daily yield, L/d	16.5	17.2	12.1	21.3	6.9
Unproductive days	875	858	779	956	131
Days in profit	506	337	0	840	552
Breakeven age, days	1,291	1,283	1,240	1,337	80
Profitable life, %	23.4	22.0	0	40.6	20.3
Productive life, %	44.5	47.1	34.6	57.0	15.8
Culling age, days	1,758	1,656	1,259	2,190	650
Lactation of culling	2.9	3.0	2.0	4.0	1.7

There was no effect of AFC on lifetime production or longevity (Table 8.4). However, heifers calving before 700 days (23 months) had significantly fewer unproductive days, reached their breakeven age sooner and spent more days in the milking herd and in profit. Therefore, they had a significantly greater productive and profitable life, spending 8.2% and 9.7% more of their lives lactating and in profit respectively, then heifers calving after 852 days (28 months).

Table 8.4: Mean (standard error) lifetime performance data in culled heifers born between 2007 and 2018 (n=679), according to age at first calving; Early: <700 days (<23 months), Target: 700 to 760 days (23 to 25 months), Late: 760 to 852 days (25 to 28 months) and Very Late: >852 days (>28 months)

	Age at first calving				P
	Early	Target	Late	Very Late	
No. animals	132	232	234	81	
Lifetime milk yield, L	33,274 (1920)	31,939 (1448)	33,599 (1442)	30,443 (2450)	NS
Lifetime days in milk, d	925 (50.5)	861 (36.7)	878 (36.9)	799 (59.9)	NS
Lifetime daily yield, L/d	17.3 (0.60)	16.3 (0.45)	16.6 (0.45)	15.1 (0.76)	NS
Unproductive days	779 (9.3) [a]	852 (7.3) [b]	908 (7.5) [c]	997 (13.4) [d]	<0.001
Breakeven age, days	1184 (3.0) [a]	1262 (1.9) [b]	1329 (1.9) [c]	1438 (3.4) [d]	<0.001
Days in profit	588 (45.4) [b]	515 (27.7) [b]	501 (26.2) [ab]	385 (39.3) [a]	0.013
Profitable life, %	28.1 (2.12) [b]	23.6 (1.33) [ab]	22.6 (1.23) [ab]	18.4 (1.92) [a]	0.016
Productive life, %	48.3 (1.36) [b]	43.9 (1.03) [ab]	44.4 (1.03) [ab]	40.1 (1.74) [a]	0.003
Culling lactation	3.2 (0.15)	2.9 (0.11)	3.0 (0.11)	2.6 (0.17)	NS
Culling age, days	1714 (55.1)	1726 (41.7)	1800 (42.5)	1805 (72.3)	NS

[abc] Statistical significance (p<0.05) is reported with different letters

8.3.3 Longevity and exit reasons

Longevity of heifers, grouped by AFC, is shown in Figure 8.1. There was no short (p=0.380) or long-term (p=0.476) effect of AFC on longevity. Early calving heifers left the herd at the youngest age (median: 1790 days, 95% confidence interval: 1633 – 1958 days), followed by heifers that calved on target (median: 1808 days, 95% confidence interval: 1663 – 1888 days) and very late heifers (median: 1816 days, 95% confidence interval: 1615 – 1967 days), with late heifers remaining in the herd longest (median: 1876 days, 95% confidence interval: 1813 – 1957 days). The probability of surviving long enough to repay rearing costs was 81.4% in early calving heifers, 77.9% in late calving heifers, 77.0% in heifers calving on target and 75.4% in very late calving heifers.

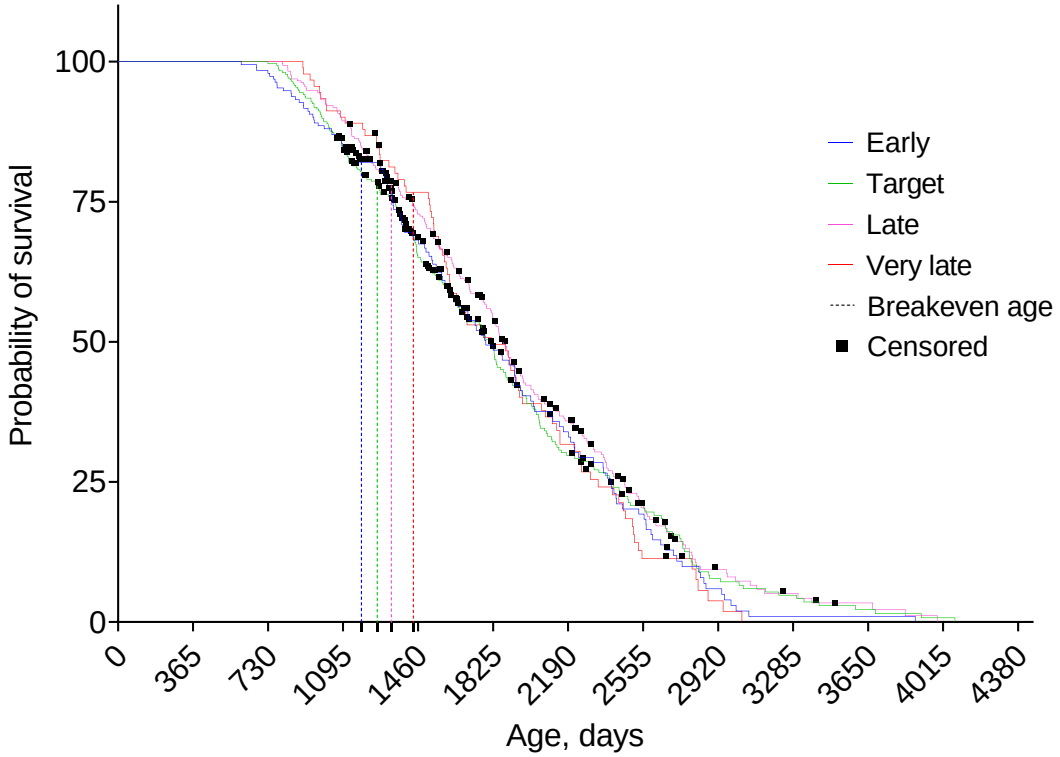


Figure 8.1: Survival of 679 culled heifers and 204 censored heifers grouped according to age at first calving. Dotted lines show mean breakeven age when a heifer repays rearing costs: Early = 1184 days, Target = 1262 days, Late = 1329 days and Very late = 1428 d.

■ Censored is defined as cows that have not been culled

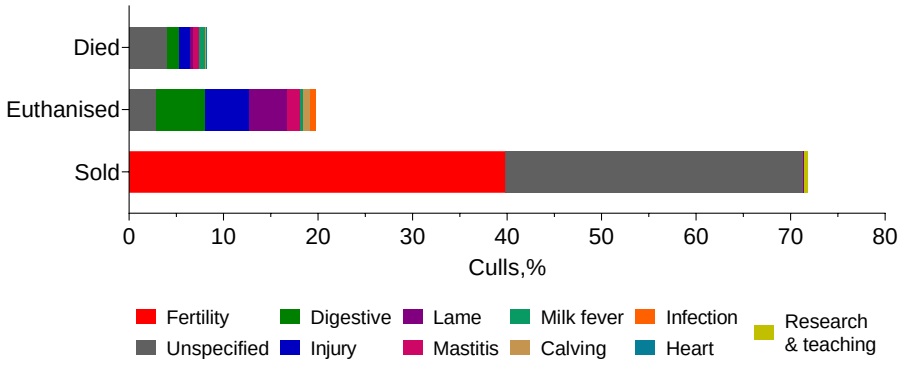
Mortality in the first lactation averaged 22.9% (Table 8.5) and there were no differences between calving groups (Pearson chi-square value = 25.65 with 25 d.f., p=0.371). Heifers calving on target and late reached a maximum of Parity 9, whereas heifers calving early reached a maximum of Parity 8 but had the greatest survivability to Parity 5 (IQR: 2 to 5). No heifer calving very late survived beyond Parity 6 (IQR: 2 to 4).

Majority of herd exits were recorded as sold (71.9%), followed by euthanised (19.9%), died (8.2%) (Figure 8.2a). The major exit reasons were fertility (39.8%) and unspecified (38.3%), followed by digestive (6.3%), injury (5.9%) and lame (4.6%) (Figure 8.2b).

Table 8.5: Cumulative mortality (%) between lactation one to nine from 679 culled heifers born between 2007 and 2018. By age at first calving; Early: <700 days (<23 months), Target: 700 to 760 days (23 to 25 months), Late: 760 to 852 days (25 to 28 months) and Very Late: >852 days (>28 months)

Lactation	Age at first calving				Mean mortality
	Early	Target	Late	Very late	
1	20.5	25.0	22.6	23.5	22.9
2	42.4	48.3	43.6	55.6	47.5
3	62.1	69.0	67.5	74.1	68.2
4	73.5	83.2	82.5	90.1	82.3
5	87.1	90.1	93.2	98.8	92.3
6	97.0	94.8	97.0	100.0	97.2
7	99.2	98.3	98.7	100.0	99.1
8	100.0	99.6	99.6	100.0	99.8
9	100.0	100.0	100.0	100.0	100.0

(a)



(b)

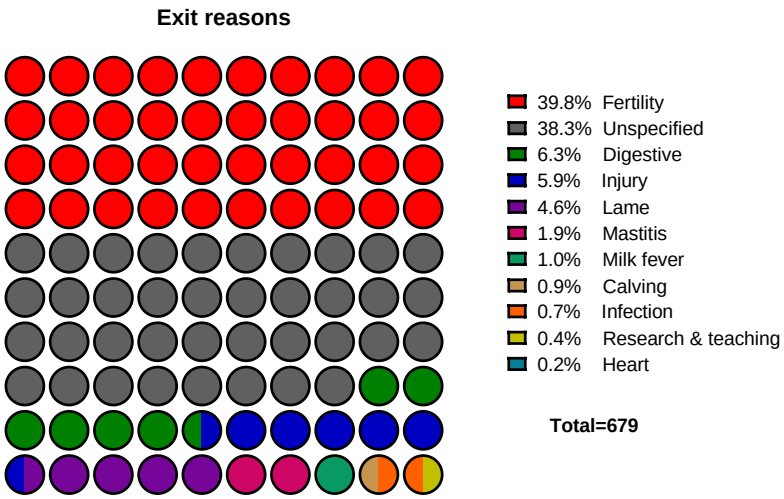


Figure 8.2: Exit reasons according to (a) exit group and (b) as an overall percentage from 679 culled heifers born between 2007 and 2018

8.4 Discussion

This study evaluated effects of AFC on first lactation and lifetime performance, age when rearing costs are repaid, and longevity in the herd. Specifically, evaluating performance of heifers calving before the target age of 730 days (24 months), which has been previously shown to perform less well in comparison heifers calving on target.

8.4.1 First lactation performance

Results of this study support previous authors who report lower first lactation milk yield in heifers calving at a younger age. Heifers calving before 700 days (23 months) were lightest at first calving, so consequently had higher DLWG and gained a greater proportion of LWFC during first lactation. This was expected as these heifers were under-mature at first calving. Analysis of growth trajectories in dairy cows until the end of the third lactation showed that growth continues throughout this entire period, although DLWG reduces at approximately 450 days of age (Coffey *et al.*, 2006). Therefore, heifers calving earlier must continue maturing to a greater extent after calving and partition a larger proportion of energy towards growth at the expense of milk production and potential fertility. A study that compared heifers reared to calve at 730 to 760 days (24 to 25 months), but with differing LWFC (540 or 620 kg), concluded that heifers with lower LWFC had lower first lactation milk yield but similar second and third lactation milk yields, and were more economic overall (Dawson and Carson, 2004). Increasing LWFC of early-bred heifers will reduce DLWG during first lactation and partition more energy for milk production. Enhanced early growth is therefore essential for heifers to calve before 700 days (23 months) with adequate maturity and LWFC.

On the other hand, heifers calving after 852 days (28 months) had the highest MW%, which was above the target range, indicating that these heifers had become too large. Heifers calving with higher body condition at calving subsequently mobilise more tissue, which negatively impacts fertility (Wathes *et al.*, 2008). The current study found that heifers calving before 700 days (23 months) had better fertility in first lactation than later calving heifers and

returned to cyclicity faster as they were diagnosed pregnant sooner than any other AFC group. This contradicts previous studies that reported lowest conception rates in heifers calving between 700 and 760 days (23 and 25 months) (Ettema and Santos, 2004), and shortest subsequent calving intervals in spring calving Irish heifers calving at 760 to 791 days (25 to 26 months) (Evans *et al.*, 2006). As a result, early calving heifers in the current study had a shorter calving interval, which may have contributed to lower first lactation milk yield.

8.4.2 Lifetime performance and longevity

One of the key findings of this study was that heifers calving before 700 days (23 months) repaid their rearing costs earlier and spent the greatest proportion of their lives lactating. Heifers do not become profitable until 530 days post-calving or halfway through their second lactation (Boulton *et al.*, 2017), and this study found that early calving heifers were most likely to calve a second time and repay their rearing costs. Unexpectedly though, there was no effect of AFC on lifetime milk yield or longevity. It has been reported that younger calving heifers produce more milk over their lifetime and remain in the herd longer (Cooke *et al.*, 2013), although not if they calve before 639 days (21 months) (Nilforooshan and Edriss, 2004). In the current study, the lack of effect of AFC on milk production and longevity was accompanied by greater profitability of earlier calving. As early calving heifers repaid their rearing costs soonest but spent the same time on farm as the older calving groups, these heifers had the greatest number of days producing profitable milk. Additionally, early calving heifers were more likely to calve a second time and a greater proportion exceeded their breakeven age.

The lack of effect of AFC on lifetime milk yield and longevity in the current study supports the economic penalty of calving later than 852 days (28 months). This is because there is no production gain from an older AFC, but there are increased rearing costs associated with calving later, as Chapter Four and other studies have reported (Pirlo *et al.*, 2000; Tozer and Heinrichs, 2001; Boulton *et al.*, 2017; Eastham *et al.*, 2018). Although there was no significant effect of AFC on production and longevity parameters, very late calving heifers spent the

greatest number of days unproductive and had the lowest productive index. Therefore, very late calving heifers spent the lowest proportion of their lifetime in milk whilst spending the same time on farm as earlier calving heifers. Additionally, as very late calving heifers entered the milking herd latest, they were significantly older when they repaid their rearing costs earlier and had a lower profitable life. This meant that a great number of early calving heifers spent a longer time producing profitable milk. Additionally, it is likely that heifers calving after 852 days (28 months) took longer to return to cyclicity, because they had longer than average calving intervals (396 days versus UK median of 388 days) (Hanks and Kossaibati, 2020). Together, these results support the proposal that it is more economical to rear heifers to calve at younger ages and that younger heifers will have better survival rate to second calving and beyond.

A large proportion of heifers did not have a specified exit reason, so it was not possible to determine causes of cows leaving the herd. This may explain the unexpected lack of significant effect of AFC on lifetime performance and longevity. It is speculative, but perhaps a reason was not specified at the time of culling if a cow was healthy. Reasons may then include low milk yield, age, temperament, udder conformation, or barren, which may be likely as fertility was the major culling reason in this herd. Additionally, cows may by culled to make room for heifers to enter the herd, however this may be an unlikely reason from 2016 when expansion of the herd began. Cows were on average 1738 days (4.8 years) when they left the herd, completing 2.9 lactations with a productive life of 872 days (2.4 years). This is over 400 days fewer than the UK median age of exit (2190 days) and productive life (1350 days), and less than the national median of 3.5 lactations (Hanks and Kossaibati, 2020). An earlier exit could be due to the productivity of this herd, which over the study period had an average milk yield of 17.0 kg/d and 11,419 kg per lactation and is higher than the national herd average in 2020 of 12.8 kg/d and 8,904 kg/year (Hanks and Kossaibati, 2020). Higher yielding cows are associated with lower fertility, which may explain why cows in this herd completed fewer lactations and left earlier. Additionally, many cows in this database were housed in the old milking barns which was not optimum for high yielding cows, so some cows may have been culled because they did not fit the AMS. Better recording of reasons for

herd exit is recommended for improved herd management. Often a reason is not specified at time of culling because the animal is healthy, and cows might be culled to make room for heifers to enter the herd.

8.5 Conclusion

This study highlighted that heifers calving before 700 days (23 months) spent a greater proportion of their lives lactating. These heifers were most likely to calve a second time and spent greater days producing profitable milk. Heifers failing to survive their first lactation are uneconomical to rear, and herd profitability would increase if more heifers survived beyond their first lactation. Early calving heifers were most likely to conceive within 100 days of calving in their first lactation, which contributes to shorter calving interval and higher reproductive efficiency. First lactation yield increased with AFC, however, there was no difference in lifetime performance and longevity of heifers calving before or after 700 days (23 months). Exploration of exit reasons could not explain this finding, and better recording of reason for herd exit is recommended for improved herd management. This study suggests that rearing heifers to a greater maturity and LW when calving at 700 days (23 months), would increase energy partition for milk production instead of growth during first lactation, and would improve herd profit from increased milk yield returns and reduced rearing costs.

Chapter 9

General discussion and conclusions

This research used heifers and high-yielding cows in an all-year-round (AYR) system to assess factors during the rearing period that contribute to whole-farm feed efficiency. This chapter will conclude the study by summarizing the key research findings in relation to the research aims and discussing the value and contribution thereof. It will also review the limitations of the study and propose recommendations for future research.

9.1 Summary of findings

The aims of this thesis centred on the age at which a heifer begins her productive life. Age at first calving (AFC) is recognised as a key performance indicator in the dairy industry, but the proportion of systems achieving the 730 days (24 months) target has remained low. To provide a starting point, Chapter Three set out to quantify variation in AFC in the study herd, as well as live weight (LW) and maturity at first calving which have been shown to be perhaps of greater importance (Margerison and Downey, 2005). Heifers calved, on average, at 757 days (24.9 months) and with 87.5% mature weight (MW), meeting age and LW targets, but there was large variation within and between yearly averages. This supports the conclusion of Brickell and Wathes (2011) that high variation exists even in heifers born on the same farm and that universal targets may be unsuitable since each farm has a unique management strategy and environmental conditions (Wathes *et al.*, 2014). Furthermore, the proportion of heifers achieving age and LW targets at calving was low in this herd, which needs to be considered when evaluating heifer rearing efficiency and targets. It is therefore important to identify causes of extremes in AFC and LW at first calving (LWFC) on an individual herd basis. Although variability cannot be eliminated, these causes may be adding to greater rearing costs, management challenges, and reduced efficiency. Therefore, looking beyond performance means can expose inefficiencies of variation.

In response, Chapters Four, Five and Six explored the influence of disease, growth and fertility on AFC and future performance. As oral rehydration solutions are not recorded as medicinal, the effect of gastrointestinal enteric disorder (GED) could not be studied in historic heifers. Additionally, as heifers

in the study herd were not weighed, Chapter Five could not look at effects of disease on growth. Therefore, Chapter Four set out to analyse GED incidence in pre-weaned calves and effects on feed intake and behaviour as a tool in the early detection of disease. In the UK, GED incidence is poorly recorded, but estimates from other countries suggest a rate between 11 and 25% (Johnson *et al.*, 2021). In the study herd, GED could be described as low severity but highly prevalent in the study herd, affecting four in ten calves for 2 days on average. GED was most prevalent between 10 and 15 days of age and significantly reduced milk replacer intake and daily LW gain (DLWG) in the first four weeks of life. This impact on intake and growth can be detrimental to achieving rearing targets as this is the period of greatest feed conversion efficiency (Bach and Ahedo, 2008). Therefore, producers need to be most diligent regarding calf health during the first four weeks of life when calves are most vulnerable to disease. Reduced DLWG could not be compensated later in heifers with GED and, as a result, weaning LW was reduced by 10%, which may affect subsequent fertility and AFC (Buskirk *et al.*, 1995; López *et al.*, 2018). Reduced milk replacer intake and greater unrewarded visits were associated with calves with GED and demonstrated a potential suitability for early indicators of disease. Integration of these measures into an automated system could enable rapid intervention including use of preventative oral rehydration solution. In addition to facilitating on-farm decision-making, development of such tools would reduce treatment and rearing costs, and achieving higher DLWG in the first four weeks of life will improve feed efficiency and heifer performance.

Chapter Five was the second of two health studies and investigated the impact of bovine respiratory disease (BRD). BRD is reported to delay AFC, but the extent of this delay ranges between 8 days (Bach, 2011) to 6 months (Correa *et al.*, 1988). The current study found heifers that required ≥4 treatments for BRD calved 41 days later and incurred an additional £708 which increased estimates of rearing costs by 39%. This was predominantly due to lower milk yield return, followed by costs of greater days rearing, which may reduce whole-farm feed efficiency (WFFE) as extra feed is consumed by an unproductive animal. In many studies, BRD either does not affect milk yield (Britney *et al.*,

1984; Warnick *et al.*, 1997; Schaffer *et al.*, 2016; Teixeira *et al.*, 2017b; Abuelo *et al.*, 2021; Hurst *et al.*, 2022) or reduces milk yield (Schaffer *et al.*, 2016; Buczinski *et al.*, 2021). Therefore, it was surprising to find that BRD increased subsequent milk yield and longevity in the current study. As a result, the gain in lifetime performance in heifers receiving multiple BRD treatments (≥4) outweighed the increase in rearing costs. It was thought that perhaps cows sustaining BRD in early life acquired protective factors through stimulation of the immune system. However, results from Chapters Six and Eight suggest cows that did not require BRD treatment as a heifer may have left the herd early due to infertility. Nevertheless, BRD incidence was greatest in heifers between 30 days and 6 months of age and from December to February. This corresponded with weaning and the winter period when conditions are seasonally colder and wetter. Therefore, BRD prevention methods should focus on minimising stress around weaning and maintaining a well-ventilated, thermo-neutral environment throughout winter, particularly in pre-weaned heifers.

Disease is also associated with poor fertility (Svensson and Hultgren, 2008; Wathes *et al.*, 2008; Hultgren and Svensson, 2010), therefore, the current study then set out to determine if variation in AFC is a result of poor heifer fertility, or a management decision to defer mating of some heifers. Chapter Six confirmed that poor fertility as a heifer delays AFC and continues into adulthood which detrimentally affects herd performance. The findings indicated that mating of heifers was based on age, at approximately 445 days, and not maturity as recent studies recommend (Margerison and Downey, 2005). However, this is not uncommon, and heifers with poor fertility were those with the lowest estimated maturity (46% MW) at first service. Heifers that took longer to conceive entered the herd 99 days later and exceeded the maturity target of 85-90% MW at calving which reduced their lifetime milk production and profitability. This was because heifers with poor fertility were older at conception during first lactation, were less likely to calve a second time, and spent a smaller proportion of their life lactating. These heifers are uneconomical to keep. Therefore, this research suggests that rearing heifers that are not mature for mating by 450 days (14.8 months) significantly reduces efficiency of the overall

system through delayed calving, increased rearing costs and poor first lactation fertility and are least likely to survive to payback their rearing costs.

More progress should be made on farms to achieve high growth rates for all heifers, so they are of adequate body size and maturity before first service. Utilising LW targets and growth monitoring would help dairy farmers to optimise heifer management and increase success of their replacement programme. However, good quality nutrition is imperative to attaining optimum heifer growth. The effect of feeding level varies with age and can be categorised into stages of pre-weaning; weaning to conception; and conception to calving. The pre-weaning period is the most expensive stage of rearing and feed costs contribute the greatest during this period (46%; Boulton *et al*., 2015a) due to milk feeding. Nevertheless, as feed conversion efficiency is at its highest in the first nine weeks of life (50%; Bach and Ahedo, 2008), feeding elevated levels of good-quality milk replacer is most effective in terms of growth. Moreover, the findings of Chapters Four, Five and Six support the consensus that feeding for greater growth rate can decrease disease incidence, improve fertility, and reduce AFC. Therefore, costs associated with putting sufficient resources into rearing well-grown and healthy heifers will be recouped later by producing cows with greater lifetime profitability.

It is important that that heifers calve with sufficient maturity to prevent negating benefits of an earlier AFC and to successfully integrate into the milking herd. Therefore, Chapter Seven aimed to address how to minimise challenges during first lactation. Social hierarchy is natural within a dairy herd (Neave *et al.*, 2017), however, Chapter Seven found that behaviours such as increased activity, low rumination and short feeding duration can be indicative of cow competition and displacement. Furthermore, certain feed behaviours, such as meal size and feeding rate, restricted heifer dry matter intake (DMI) which limits their ability to reach their milk yield potential. As heifers continue to grow throughout their first lactation (Coffey *et al.*, 2006), a lower milk yield was expected compared to mature cows. However, it is still critical to encourage greater DMI in the first lactation so that heifers reach full maturity sooner and can allocate more energy for milk production. Primarily, this must be supported by growing heifers

efficiently so that they calve at the correct LW, and also ensure heifers in their first lactation have enough time to feed and lie down throughout the day. An automatic milking system (AMS) gives cows greater free choice to organise their time budget (Olofsson *et al.*, 2000), however, stocking density, feeding space and design, and feed availability are still important in reducing competition and displacement so that heifers in their first lactation can spend longer eating and resting. Increasing feeding time and reducing feeding rate have been associated with greater digestibility and feed efficiency (Llonch *et al.*, 2018; Krpálková *et al.*, 2021). This study suggested identifying high-yielding cows with these feed behaviours to develop automated tools in assessing feed efficiency in dairy systems. Additionally, alternatives such as nutritional grouping or housing heifers in first lactation separately, could provide an environment for heifers to achieve and maintain high DMI throughout their first lactation. This will help heifers realise their milk yield potential and return investments made in the rearing period sooner.

Because heifers entering the milking herd for the first time are particularly vulnerable to stressors, the risk of health and fertility issues resulting in premature culling is increased. To return her rearing cost, a heifer must survive beyond 1.5 lactations on average (Boulton *et al.*, 2017), however, in the study herd one in five heifers that reached first calving did not calve for a second time. This is double the recommended mortality rate in first lactation of 10% (Breen *et al.*, 2012) which further reduces farm profitability. Therefore, Chapter Eight addressed the final aim of the thesis to assess effects of AFC on lifetime performance and longevity. Heifers calving before 700 days (23 months) spent a greater proportion of their lives lactating. These heifers were most likely to conceive within 100 days of calving in their first lactation, which contributes to shorter calving interval and higher reproductive efficiency. However, there was no difference in lifetime performance and longevity of heifers with AFC before or after 700 days (23 months). Exploration of recorded exit reasons could not explain this finding, and better recording of reason for herd exit is recommended for improved herd management. Findings from Chapter Six suggest some variation in survivability and lifetime performance is due to poor fertility. Culling rate is determined indirectly by success of heifer rearing. Poor fertility

management has a high opportunity cost and wastage of barren cows which are otherwise of good genetic merit and/ or high yielding needs to be considered. There is increasing awareness around 'production' diseases, poor welfare and wastage in dairy herds which can be associated with poor fertility and economic efficiency. These diseases include dystocia, milk fever, endometritis, lameness, and mastitis which have higher incidence in higher yielding cows with greater genetic merit (Esslemont and Kossaibati, 1996; Dobson *et al.*, 2007; Dobson *et al.*, 2008; Mulligan and Doherty, 2008). This study suggests that rearing heifers to a greater maturity and LW when calving at 700 days (23 months), would increase energy partition for milk production instead of growth during first lactation, and would improve herd profit from increased milk yield returns and reduced rearing costs. These results suggest that calving at 700 days (23 months) is optimum for this herd.

9.2 Industry impact and application

Data on heifer management in the UK are lacking, specifically in high-yielding and AYR systems, therefore the effects of current heifer rearing practices on future performance are largely unknown. For many years the universal target for age at first calving has been 730 days (24 months); however, most farms are still not achieving this. This research set out to find explanations for late and/or varied AFC to provide strategies that improve heifer rearing efficiency and farm profitability. Key outcomes from this research for the dairy industry focus on calculating targets on an individual herd basis. This was found to be important not only when calculating MW targets for heifer growth monitoring, but also for herd performance. For example, an AFC of 700 days was optimum for the study herd as heifers calving early were in calf sooner and had a greater productive life. At the farm level this will increase WFFE as the number of days feeding non-profitable heifers is reduced, rearing costs are returned sooner and there is a greater milk return from a longer productive life. This will have a positive environmental impact on a global level as an earlier AFC requires fewer replacement heifers which, when combined with greater lifetime production and longevity, dilutes the economic and environmental cost of rearing herd replacements.

Lastly, the findings advocate for better record-keeping and benchmarking; primarily for weighing heifers and monitoring DLWG to assess achievement of growth targets, but also for recording heifer health and reason for herd exit to reduce heifer mortality and involuntary culling. A limitation to UK dairy systems recording heifer growth is access to suitable weighing facilities. Research and industry should be encouraged to work collaboratively to provide solutions to this and emphasise the shift in focus from AFC to meeting maturity targets throughout the rearing period. Recommended time points for weighing heifers are at birth, weaning and pre-mating, however good practice is every 4 to 8 weeks, particularly in younger heifers. This is because necessary growth rates are a higher percentage of body weight at a young age, and it is therefore more difficult for heifers to catch up if they fall behind early. Ensuring heifer growth and morbidity data are routinely collected on-farm will serve to provide information not only to producers and advisors on a farm level basis but also to industry with a more comprehensive understanding of calf health. Without this information, it is far more challenging to identify key obstacles facing optimal heifer calf health and productivity. By doing so this may provide a better understanding to why some heifers leave the milking herd before they have repaid their rearing costs. Poor fertility and a low milk yield in the first lactation is observed across the dairy industry, however, this research has also identified behavioural strategies to encourage greater DMI during the first lactation, which is needed to achieve the correct energy balance, regain cyclicity and attain higher milk yields.

9.3 Study limitations

A limitation to this work is that for all the chapters, except Chapters 4 and 7, is that data presented are retrospective and could be confounded by unrelated management interventions. Another limitation is that heifers in the study herd were not routinely weighed, therefore results for DLWG and maturity before first calving are estimated.

Another consideration is data are from only one herd, which is a research herd so is not an accurate representation of all high-yielding and AYR systems in the

UK. Unfortunately, this research was interrupted and delayed halfway through the project due to the global Covid-19 pandemic. This study would have otherwise included data from other herds using Lely AMS to create a more comprehensive database. Following this, caution is advised if extrapolating this data to other breeds, feeding systems, housing systems and calving patterns.

In Chapter Five, data collection was limited by animal information historically recorded on the Uniform database, which was not routinely uploaded until 2014, thus resulting in a small sample size, particularly for lifetime analyses of BRD treatment. Lifetime data are otherwise difficult to collect in large animals and the average lifespan of a dairy cow would exceed the length of this study. Similarly, the number of animals used to study GED in Chapter Four was small as the housing capacity of the heifer shed restricted sample size. Additionally, since heifers were housed in pairs, measurements for straw, concentrate and water intake were based on a pen basis, so does not represent an accurate individual measurement.

9.4 Recommendations for future research

The results of this study are based on a high-yielding and AYR system. To build on this data, it is recommended to repeat the study using herds operating different systems in the WFFE model. For example, grass-based, block-calving, and conventional (six months grazing, six months housed, AYR calving) systems. This research also identified behavioural measurements which would require further experimentation before development as an on-farm tool. For example, milk replacer intake and unrewarded visits to the automatic calf feeder were associated with GED in heifers in Chapter Four, and meal frequency and meal duration were associated with feed efficiency in lactating cows in Chapter Seven. Integration of these measures into an automated system could aid in decision-making of animal health and farm performance. Lastly, BRD was unexpectedly positively associated with BRD in Chapter Five. This effect is not reported in the literature and therefore requires further research.

9.5 Key takeaways

The work in this thesis has highlighted several factors to rearing heifer replacements which affect whole-farm feed efficiency:

I. Mean age and maturity at first calving were on target but only 10% of heifers met both targets and there was a long tail to the age and LW distributions. Shortening this tail and tightening the distributions would be beneficial for efficiency.
II. Four in ten calves contracted GED for two days between 10 and 15 days of age on average. GED reduced milk replacer intake by 1.0 L/d and DLWG by 0.14 kg/d in the first four weeks of life and decreased weaning LW by 10%.
III. GED reduced milk replacer intake and unrewarded visits to the ACF, which have potential to be developed into automated tools for early indication of disease.
IV. BRD delayed AFC by 41 days, increasing estimated rearing costs by £880 per heifer (48%).
V. Poor heifer fertility increased age at first calving, worsened into adulthood and reduced longevity. Heifers that took more than 50 days after first service to be diagnosed pregnant had low estimated maturity at first service, were older at calving, took longer to conceive during first lactation and were less likely to calve a second time.
VI. Heifers calving with insufficient maturity had reduced performance in first lactation.
VII. Providing an environment where heifers are not restricted by competition from older cows, and have ample time to eat and rest when they first enter the milking herd is necessary to achieve and maintain high DMI in first lactation.
VIII. Heifers calving at 700 days conceived sooner in their first lactation, repaid their rearing costs earlier and spent a greater proportion of their life lactating, suggesting a target AFC of 700 days is appropriate for this herd.

In summary, the most efficient heifers in this herd are those that calve at 700 days with sufficient maturity and are fertile. The significant impact of AFC on returning rearing costs, lifetime productivity and replacement rate must encourage dairy systems to calve at an age and LW to optimise these factors. The findings of this PhD thesis support the consensus that feeding for greater growth rates can decrease disease incidence, improve fertility, and reduce AFC. Therefore, costs associated with putting sufficient resources into rearing well-grown and healthy heifers will be recouped subsequently by producing cows with greater lifetime profitability. This PhD thesis concludes that increasing the proportion of heifers achieving individual herd calving targets, improves heifer rearing efficiency and lifetime herd performance.

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