Rearing Strategies for Dairy Heifers

A Thesis Presented for the Degree of Doctor of Philosophy

by

Hazel Costigan

Department of Science

[1]*Dept. of Science, Waterford Institute of Technology, Cork Rd, Waterford, Co. Waterford*

[2]*Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork*

Supervisors

[1]Dr. Siobhán Walsh [2]Dr. Emer Kennedy

Submitted to Waterford Institute of Technology, September, 2021

Declaration

Title: Rearing strategies for dairy heifers

Name: Hazel Costigan

Student ID Number: 13316236

Supervisors: Dr. Siobhán Walsh and Dr. Emer Kennedy

Declaration:

"*I hereby declare that this Doctoral Research Degree Thesis is entirely my own work and that it has not been submitted for any other academic award, or thereof, at this or any other education establishment*"

Hazel Costigan

____

Hazel Costigan

Acknowledgements

I would like to acknowledge all of those who made the completion of this thesis a reality. I wish to acknowledge the fantastic opportunity afforded to me to complete this thesis at both the Animal & Grassland Research and Innovation Centre at Teagasc Moorepark and Waterford Institute of Technology. I would like to thank Dr. Pat Dillon, the Head of Centre, for the facilities and resources made available to me. I would also like to acknowledge the Teagasc Walsh Scholarship program and the Department of Agriculture, Food, and the Marine for funding my research under the MultiRepro project (15/S/696).

I would like to express sincere thanks to my research supervisor Dr. Emer Kennedy for her guidance and support, both during trial work and in the writing of this thesis; you knew exactly when I needed tough love and when to give me praise and encouragement. From teaching me how to do snips in your back garden with baby Aoibheann to preparing me for interviews on the floor of your sitting room with baby Muireann, you have certainly taught me the value of hard work and dedication. I hope that someday I will be as passionate about my job as you are about yours. I would also like to sincerely thank my WIT supervisor, Dr. Siobhán Walsh, for always supporting me from afar, particularly at the end in helping me get this thesis over the line. It was so reassuring to know that your help and expertise were a text or a phone call away. I think that, together, the three of us made a fantastic team, and I am confident that my career in agriculture is promising with both Emer and Siobhán as my mentors.

A massive thank you to Ricki, Willie, Cora, James, Finn, Eugene, Mark, and Pa on the Dairygold Research Farm in Kilworth; without a doubt, the first three years of my

Ph.D. were the most enjoyable, and that was due to all the laughs we had, both in Kilworth and Mitchelstown. I would like to mention Ricki Fitzgerald and Willie Hennessy in particular; there was no job too big or too small, and you were always so kind and patient despite the huge disruption to your jobs because of my trial work. Thanks to all the placement students who have helped me over the years but especially Chloe, Justin, Peter, Richie, and Aidan. You made my life a lot easier and gave me lots to laugh about along the way, and for that, I will be eternally grateful.

A special thanks to all of the staff in the grassland laboratory, in particular Michelle, Andy, and Pat, for all their help with my trial work over the years. I really tried to shake things up with the calf, and heifer intake runs, but you took it in your stride, and always with a smile and a few laughs along the way. Thank you also to Luc Delaby for coming on board with my project in my hour of need. Your statistical wisdom and your enthusiasm for my research were very much appreciated.

To Orlaith, Fionnuala, Alison, and Ellen thank you for making this experience so enjoyable for me. You were always there for me when I needed cheering up and even more so when there was something to celebrate. How lucky am I to have made such fabulous friends with similar interests (i.e., agriculture, Chinese food, prosecco, antipasti, cocktails and hot tubs). The industry is lucky to have the contribution of such fantastic women in agriculture.

To all the Ph.D. students in Moorepark past and present, but particularly Orlaith, Fionnuala, Alison, Ellen, Sarah, Caitlin, Brid, Aisling, Katie, Sophie, Tasha, Mossy, David, Ben, Johnny, thank you so much for all the help, support, and laughs over the past four years. Thank you also for making the dreaded trek out to Mitchelstown to help with intake runs.

Eibhan, thank you from the bottom of my heart for all your love and support, especially over the past four years. From all your help with trial work and statistics, to giving me lots to look forward to every weekend, and everything in between, I could not have done it without you. I look forward to making it up to you over the next few years.

To Mam, Dad, Edel, and Ciarán, thank you for all your support and for your willingness to help me in any way you could. Mam and Dad, thank you for showing me the value of hard work from a young age and instilling in me a love of farming. You have provided me with every opportunity in life and, without both of you, I would not be where I am today. To Granny and Maggie, thank you for all the prayers you have said and the candles you have lit for me over the past four years. Thanks also to Grandad, who probably sparked my interest in calves in the first place; although he unfortunately never got the chance to see me graduate as a “doctor of calves,” I am sure he has been looking down on me all this time.

Abstract

Replacement heifer rearing is one of the most important tasks on a dairy farm due to the cost it incurs and the potential benefits that may arise in terms of heifer growth and performance thereafter. A successful heifer rearing strategy prioritizes DMI, BW, and frame size of the heifer; however, consideration must also be given to the way in which a heifer is managed. Therefore, the aim of this thesis was to establish the effect of different heifer rearing strategies on aspects of pasture-based heifer growth. An experimental field study was carried out to investigate the effect of weaning age (eight or 12 weeks) and post-weaning feeding regime (high or low) on the DMI, growth performance, and reproductive efficiency of pasture-based heifers of different breed groups. Results in Chapters 3, 4, 5, and 6 indicated that although heifer DMI, BW, and frame size differed with breed group, they were highly susceptible to the post-weaning feeding regime, irrespective of weaning age. This finding has positive practical significance for pasture-based dairy farmers as it indicates that post-weaning feed management can be manipulated to ensure that weight-for-age targets are achieved. Pasture-based heifer DMI throughout the rearing period was quantified in Chapter 3, and the resulting data were used to create an equation to predict the DMI of HF and JE using BW as a proxy.

An accurate DMI prediction equation will assist pasture-based dairy farmers in optimizing pasture allowances and thus increasing the efficacy of pasture utilization. In Chapter 4, an equation was created to determine the growth trajectory of pasture-based HF and JE; this equation showed that pasture-based heifer growth was sigmoidal in shape. Furthermore, the use of this equation to create additional weight-for-age targets for pasture-based heifers will optimize heifer growth prior to the commencement of the breeding season. A separate equation was created in Chapter 6 to predict heifer BW using a series of LBM; this facilitates the monitoring of heifer growth in the absence of a weighing scale. Findings in Chapter 5 suggested that growth pattern throughout the rearing period is an important determinant of reproductive performance, the efficiency of which was impeded when feed allowance fluctuated between the pre and post-weaning periods and when heifers were ahead of target BW at breeding.

Furthermore, by using an external dataset of 1,323 heifers across 2,924 parity one to three calving events, the associations between AFC and BW at first calving of pasture-based heifers were quantified. Findings indicated that BW at first calving had a greater impact on performance in the lactating herd than that of age. Moreover, BW at first calving has the potential to negate the suboptimal performance that is often associated with a younger AFC. The findings in this thesis highlight the importance of management decisions on the performance of dairy heifers.

Table of Contents

List of Abbreviations

12w	12-Week Weaned
8w	8-Week Weaned
ADF	Acid Detergent Fibre
ADG	Average Daily Gain
AFC	Age at First Calving
AI	Artificial Insemination
APT	Adequate Passive Transfer
bBW	Birth Body Weight
BCS	Body Condition Score
BL	Body Length
BV	Body Volume
BW	Body Weight
CCC	Concordance Correlation Coefficient
CFS	Calving to First Service
CP	Crude Protein
DHA	Daily Herbage Allowance
DM	Dry Matter
DMD	Dry Matter Digestibility
DMI	Dry Matter Intake
EBI	Economic Breeding Index
FCE	Feed Conversion Efficiency
FPT	Failure Passive Transfer
H	High Post-Weaning Feeding Regime
HF	Holstein-Friesian

208	HG	Heart Girth
209	ICBF	Irish Cattle Breeding Federation
210	Ig	Immunoglobulins
211	IgA	Immunoglobulin A
212	IgG	Immunoglobulin G
213	IgM	Immunoglobulin M
214	JE	Jersey
215	L	Low Post-Weaning Feeding Regime
216	LBM	Linear Body Measurements
217	MR	Milk Replacer
218	MS	Milk Solids
219	MSD	Mating Start Date
220	MSPE	Mean Square Prediction Error
221	NDF	Neutral Detergent Fibre
222	OM	Organic Matter
223	RMSE	Root Mean Square Error
224	RMSPE	Root Mean Squared Prediction Error
225	RPE	Relative Prediction Error
226	SCC	Somatic Cell Count
227	SCS	Somatic Cell Score
228	TMR	Total Mixed Ration
229	WH	Withers Height
230	WM	Whole Milk

List of Tables

List of Figures

Chapter 1: Introduction

Heifers are an integral part of the herd; their rearing accounts for between 15 and 20% of total costs on a dairy farm (Pirlo et al., 2000; Gabler et al., 2000). Replacement heifer management decisions can have a profound effect on the profitability of a farm enterprise. Feed intake, and consequently, growth are the foundations on which a successful heifer rearing strategy is built (Roche et al., 2015). However, the growth and quality of grass, which is the predominant feed of a pasture-based heifer, is frequently influenced by factors outside the farmer's control, such as weather conditions throughout the grazing season (Burke et al., 2002; Waghorn & Clark 2004), which may limit animal performance (Litherland et al. 2002). Pasture-based heifers exhibit a different growth pattern to that of heifers reared in confinement (Handcock et al., 2021). Therefore, there may be a requirement to create best practice guidelines for managing pasture-based dairy heifers throughout the rearing period.

Much of the previous research on heifer DMI has been undertaken in confinement systems of rearing where heifers are supplied with the exact nutrient profile necessary to sustain BW gain (NRC, 2001; Zanton and Heinrichs, 2008b). In contrast, the DMI of pasture-based heifers is dependent on grassland management parameters such as pasture allowance (Patterson et al., 2018), post-grazing sward height (Ganche et al., 2013), and concentrate supplementation strategies (Patterson and Morrison, 2019). Furthermore, DMI may also differ with breed group (Prendiville et al., 2010). While an exclusively pasture-based diet can supply the nutrients required for heifer BW gain (Patterson et al., 2018), occasional concentrate supplementation may be required if grass growth and quality are poor (Roche et al., 2015). Establishing the DMI of pasture-based heifers is therefore essential to gain an understanding of growth and efficiency throughout the rearing period.

Growth is the most important aspect of a heifer rearing program; however, it is of added importance in a system with seasonal breeding and calving constraints, such as that in Ireland (Berry et al., 2013; Hayes et al., 2019). In pasture-based rearing systems, if a heifer is not the correct BW and frame size to attain puberty before the breeding season, she may not have the opportunity to be inseminated for an additional 12 months (Berry and Cromie, 2009; Hayes et al., 2019); therefore monitoring heifer growth performance is essential. This importance may be further exacerbated in heifers of different breed groups due to differences in growth (Handcock et al., 2019a).

Weight-for-age targets (Troccon, 1993) facilitate the monitoring of heifer growth throughout the rearing period. Although they were initially devised in confinement systems of heifer rearing, the aforementioned targets are utilized worldwide. Targets are dependent on mature BW; knowledge of the mature BW is required to ensure that the weight-for-age targets are appropriate (Roche et al., 2015). Heifers that are 30, 60, and 90% of mature BW at six, 15, and 24 months (Troccon, 1993) are said to have favourable performances both throughout the rearing period and in the lactating herd. Nevertheless, attainment of weight-for-age targets may vary with both feed management and breed group (Handcock et al., 2016). The 15-month weight-for-age target is particularly important in seasonal calving systems to ensure heifers have achieved puberty prior to the commencement of the breeding season, which is typically at the end of April or the start of May each year (Berry et al., 2013). Fertility improves in line with the number of estrus cycles experienced; therefore, a younger pubertal age will optimize the success of a breeding season. With that being said, nutrition and management throughout the rearing period may also influence fertility performance, such that if a heifer is too light (Brickell et al., 2009b) or too heavy (Archbold et al., 2012), lifetime reproductive efficiency may be impeded. Although the existing weight-for-age targets (Troccon, 1993) have been designed to ensure that heifers experience positive growth patterns throughout the rearing period, and as such, have achieved puberty prior to the breeding season, it is not yet known if these targets are appropriate for heifers reared in a seasonal-calving pasture-based system.

Weighing is used universally to monitor heifer growth; however, in the absence of an electronic scale, LBM may provide an accurate alternative (Heinrichs et al., 1992; Lukuyu et al., 2016). There are many measures of frame size; however, HG is the most widely used due to its high correlation with BW (Heinrichs et al., 1992). As most of the targets for heifer growth are expressed in BW, the formulation of equations to predict BW using LBM has become commonplace (Heinrichs et al., 1992; Reis et al., 2008). Furthermore, as growth varies with breed group (Handcock et al., 2019a), equations to predict the BW of pasture-based heifers of different breed groups from LBM may be required (Albertí et al., 2008). The aforementioned equations were created under confinement systems of heifer rearing and, as such, may not be appropriate for pasture-based heifers.

The current weight-for-age targets (Troccon, 1993) are widely used irrespective of the management system in place; however, different heifer rearing strategies may be required in pasture-based rearing systems in order to exploit the competitive advantage that is grazed grass (Läpple et al., 2012). Although optimal pre-weaning nutrition is vital for performance thereafter (Soberon et al., 2012b; Soberon and Van Amburgh, 2017), increasing the proportion of grazed grass in the diet will reduce the costs associated with heifer rearing (Boulton et al., 2017); consequently, reducing the length of the milk-feeding period, and introducing calves to grass earlier, may be advantageous. Furthermore, because of the disparity between the seasonality of pasture-based heifer growth (Handcock et al., 2021) and the linear pattern of growth necessitated by the existing weight-for-age targets (Troccon, 1993), supplementation in the post-weaning period may be vital to reduce pubertal age. Despite the variability of management of pasture-based heifers, the impact of rearing strategy on growth performance thereafter has seldom been discussed.

Although a younger AFC will reduce the non-productive period (Gill and Allaire, 1976), it is generally associated with suboptimal milk production thereafter (Berry and Cromie, 2009). Dobos et al. (2001) delineated that increasing BW at first calving may offset the deficits in production commonly associated with a younger AFC. However, if a heifer is too heavy at calving, there may also be unfavourable associations with calving performance (Mee, 2008b; Cooke et al., 2013) and reproductive efficiency thereafter (Roche et al., 2007c; Handcock et al., 2020). It is therefore essential to quantify the associations between AFC and BW at first calving.

Heifers are often perceived to be insignificant members of the herd because they do not contribute to farm income. At €1,545 per heifer (Shalloo et al., 2014), heifer rearing is one of the most expensive tasks on a dairy farm, second only to feed costs (Pirlo et al., 2000). The repayment of this cost only begins once the heifer enters the milking herd and is not repaid until 1.63 lactations have been completed (Berry et al., 2015). In order to obtain a good return on investment, heifer rearing must first be prioritized, and rearing strategies must then be optimized. Between 10 and 23% of heifers do not survive to first calving (Brickell and Wathes, 2011; Compton, 2018; De Vries and Marcondes, 2020). This indicates that significant improvements are required in the rearing of heifers, as these heifers are never afforded the opportunity to reimburse the cost of rearing. A further 19 and 24% of heifers are culled during the first and second lactation, respectively, with only approximately 54% of Irish heifers (Archbold et al., 2012) and 55% of UK heifers (Brickell and Wathes, 2011) calving successfully for a third time. There is a similar pattern in the United States, such that the average lifetime parity number of HF heifers reduced from 3.4 in 1989 to only 2.8 in 2004 (Nieuwhof et al., 1989; Hare et al., 2006). The reasons cited for culling were infertility (Brickell and Wathes, 2011), poor conformation, and poor health (Meier et al., 2017). Well-reared heifers, i.e., those that attain target weights at the specified time, are less likely to become ill, will have improved fertility and milk production, and are more likely to survive longer in the herd (Heinrichs and Heinrichs, 2011; Wathes et al., 2014). The aforementioned decrease in the length of the productive life is associated with an increase in heifer replacement rates, and consequently, production costs (Mohd Nor et al., 2015). Future rearing strategies must optimize heifer growth, which will, in turn, optimize productivity and thus increase the length of the productive life; doing so will have implications both financially and environmentally, as it will reduce the number of replacement heifers required.

The general aim of this thesis was, therefore, to investigate the effect of different pasture-based heifer rearing strategies on the performance of HF and JE heifers thereafter.

The main objectives of the work presented in this thesis were:

1. To quantify the DMI of HF and JE heifers reared under different management systems and devise equations to predict DMI from the BW of pasture-based HF and JE heifers
2. To determine the associations between growth and fertility of pasture-based HF and JE heifers reared under different management systems
3. To devise a series of equations to predict BW from LBM of pasture-based HF and JE heifers reared under different management systems
4. To establish the growth trajectory of pasture-based HF and JE heifers reared under different management systems, to evaluate if existing weight-for-age targets were suitable, and, if necessary, create additional targets to complement the rearing of pasture-based heifers
5. To quantify the independent associations between AFC and BW at first calving in spring-calving Holstein-Friesian dairy heifers with a series of performance metrics

The findings of this research will consolidate different rearing strategies for pasture-based dairy heifers, the like of which has not been previously investigated. The recommendations herein may be used by pasture-based farmers to streamline the heifer rearing process by increasing pasture utilization through the establishment of heifer DMI and by optimizing heifer BW through the attainment of weight-for-age targets.

Furthermore, the present research will provide a foundation for future research on the rearing of pasture-based dairy heifers.

Chapter 2: Literature Review

2.1 Pre-Weaning Calf Management

2.1.1 Colostrum

Colostrum is defined as the first milk secreted after parturition (Dukes, 1935), the feeding of which is one of the most important aspects of a heifer rearing program. Colostrum contains many nutrients essential for the health of the newborn calf (Godden, 2008), in particular, immunoglobulins. Immunoglobulins, or antibodies as they are commonly known, are proteins produced by white blood cells, which are essential for immune response (Dukes, 1935). Transfer of maternal Ig between the dam and her calf in utero is prevented due to the separation of the maternal and foetal blood supplies (Baumwart, 1976). Consequently, the calf is immunocompromised at birth. In order to achieve immunity, the calf depends entirely on the absorption of maternal Ig from colostrum after birth (McGuirk and Collins, 2004; Godden, 2008). This process is dependent upon the timing of colostrum feeding, the volume of colostrum fed, and the quality of the colostrum.

2.1.1.1 Timing of Colostrum Feeding

In the 24 hours after birth, the neonate's gut has a unique ability to absorb large proteins non-selectively, therefore stimulating passive immunity (Klaus et al., 1969; Larson et al., 1980; Stelwagen et al., 2009). Permeability of the calf gut is greatest in the first four hours post-partum (Robison et al., 1988; Weaver et al., 2000) and decreases rapidly 12 hours post-partum (Stott et al., 1979a). The cessation of absorption, which occurs on average 24 hours after birth, is termed gut closure (Stott et al., 1979a; Weaver et al., 2000). Calves fed promptly after birth (i.e., within four hours) will have significantly higher rates of Ig absorption (Stott et al., 1979b) compared to their herd mates fed between six and 12 hours later (Bush and Stanley, 1980; Besser et al., 1985). Furthermore, as the time between calving and colostrum feeding increases, so too does the risk of mortality because the calf has no protection from pathogenic bacteria in the environment (Margerison and Downey et al., 2005). In addition, colostrum production ceases at parturition, and as the time between calving and colostrum harvest increases, the quality deteriorates (Conneely et al., 2013). A 3.7% reduction in Ig concentration per hour is observed in the hours after parturition (Morin et al., 2010). The timely harvest and consumption of colostrum are therefore important.

2.1.1.2 Volume of Colostrum

The volume of colostrum fed to the calf has a significant impact on passive transfer (Hopkins and Quigley, 1997; McGuirk and Collins, 2004). Recommendations for the volume of colostrum that the calf should consume at first feeding vary considerably. Some studies advocate feeding a predetermined volume in litres (Faber et al., 2005; Chigerwe et al., 2009), a practice that may be beneficial in systems where calves are not weighed at birth. Varying the volume of colostrum fed depending on the colostrum quality is also commonplace (Morin et al., 1997; Jaster, 2005). Calves are described as having achieved APT if the serum IgG concentration is above 10 g/L in blood samples taken at 24 hours (Weaver et al., 2000; Godden et al., 2008). The absorption of approximately 150-200 g of IgG shortly after birth is necessary to achieve ATP (Godden et al., 2019). Therefore, varying the volume of colostrum fed depending on quality may be a useful tool to ensure the calf consumes a sufficient amount of IgG at birth. The calf may also be fed colostrum based on their birth BW (Godden et al., 2008; Conneely et al., 2014). The birth weight of the calf is highly variable; for example, a study carried out by

Dhakal et al. (2013) on over 1,200 calves in a nine-year period found that there was a difference of almost 15-25 kg between the lightest and the heaviest calf within a purebred breed group at birth. Therefore, feeding colostrum based on the birth weight of the calf will ensure that each calf receives sufficient colostrum for his or her size.

It is widely accepted that increasing the volume of colostrum fed to the calf will reduce the risk of FPT in calves (Besser et al., 1991). This theory is supported by Faber et al. (2005) and Davis and Drackley (1998), who found that increasing the colostrum-feeding rate would benefit the future performance of the calf. However, calves fed 8.5% of birth BW in colostrum had improved efficiency of IgG absorption relative to their herd mates fed seven and 10% of birth BW, respectively (Conneely et al., 2014). This indicates that increasing the volume of colostrum fed to the calf is only constructive up to a certain point, in this case, 8.5% of birth BW (Conneely et al., 2014), after which there may be a negative correlation between IgG absorption and the volume of colostrum fed (Besser et al., 1985).

2.1.1.3 Colostrum Quality

There is a strong correlation between Ig concentration and the quality of the colostrum (Godden, 2008). There are three classes of Immunoglobulins found in bovine milk: IgA, IgM, and IgG (Butler, 1969). Class is reflective of the source and route along which the immunoglobulins have been transmitted (Larson et al., 1980). Immunoglobulin G is selectively transported from the maternal blood supply, across the mammary barrier, and into the lacteal secretions (Butler, 1969; Larson et al., 1980). Immunoglobulins from class A and M are locally synthesized in the mammary gland and occur in colostrum, albeit in small amounts (Larson et al., 1980). Bovine IgA, IgM, and IgG account for on average 5, 10, and 85-95% of colostral immunoglobulins, respectively (Butler, 1969; Larson et al., 1980). Increased production and transfer rates of IgG prior to parturition explain the significant quantities of IgG relative to IgA and IgM present in bovine colostrum (Sasaki et al., 1976). Therefore, the concentration of IgG in colostrum is commonly associated with quality. Good quality colostrum with an IgG concentration of >50 g/L is required by the calf to acquire passive immunity (Godden, 2008).

Colostrum quality may be affected by many factors such as the breed of the dam (Muller et al., 1981), lactation number (Muller et al., 1981), the volume of colostrum produced (Guy et al., 1994), time to harvest (Morin et al., 2010) and length of the dry period (Pritchett et al., 1991). Low-yielding breeds were found to have superior colostrum quality (Conneely et al., 2013); this may be due to dilutional effects (Guy et al., 1994). This is consistent with Muller and Ellinger (1981), where they observed a higher proportion of IgG as a percentage of total colostrum for JE relative to HF.

It was traditionally believed that the colostrum produced by primiparous cows should be discarded, as it would not be of sufficient quality to feed to the calf. However, although there are positive associations between parity and colostrum IgG concentration, the majority of primiparous dams produce colostrum with an IgG value above the threshold (Conneely et al., 2013; Dunn et al., 2017). The perception that primiparous cows produce inferior colostrum may instead be because of the volume of colostrum they produce. It is widely accepted that primiparous cows produce less colostrum on a volume basis (Robinson et al., 2009; Reschke et al., 2017). However, the smaller volume of colostrum produced by primiparous cows will be more concentrated, and therefore may have a higher concentration of IgG per ml of colostrum (Conneely et al., 2013). This is comparable to differences between dairy and beef animals, whereby dilution of colostrum in high-yielding dairy breeds contributes to differences in colostral IgG concentrations at calving (Guy et al., 1994).

The length of time between calving and the harvest of colostrum may also affect the quality of colostrum. Colostral IgG concentrations decrease by up to 3.7% per hour after calving (Morin et al., 2010). Therefore, in order to maximize quality, colostrum should be harvested as soon as possible after calving (Moore et al., 2005; Conneely et al., 2013). Furthermore, colostrum quality may be influenced by dry period length. The dairy cow is traditionally dried off for up to 60 days prior to calving in order to maximize milk yield in the subsequent lactation (Kok et al., 2016). Reducing the length of the dry period is often considered as a management strategy to maximize profitability (Grummer et al., 2004); however, this practice may be to the detriment of colostrum quality (Mayasari et al., 2015) and yield (Gavin et al., 2018). Nevertheless, Dunn et al. (2017) determined that although colostral IgG was reduced when the dry period length was less than eight weeks, the concentration of IgG was above the threshold value of 50 mg/ml.

There is an inverse relationship between bacteria and colostrum quality (McGuirk and Collins, 2004). Bacterial contamination of colostrum will disrupt the absorption of IgG, so it should therefore be minimized (Godden, 2019). A total bacterial count of <100,000 cfu/ml is necessary to ensure the efficacy of IgG absorption (McGuirk and Collins, 2004). A study by Morrill et al. (2012) found that 43% of colostrum samples collected from 67 farms around America exceeded the recommended threshold for colostrum bacteria levels. Levels of bacteria growth are significant in the first six hours after harvest (Cummins et al., 2017), particularly when stored in ambient temperatures (Stewart et al., 2005).

Colostrum should therefore be preserved at ≤ 4°C to reduce bacterial contamination (Cummins et al., 2017).

2.1.1.4 Testing Colostrum Quality

Colostral weight was traditionally used as an indicator of colostrum quality; it was believed that producing < 8.5 kg of colostrum was an indicator of quality (Pritchett et al., 1991). However, more recently, radial immunodiffusion has been considered the gold standard for testing IgG concentration in bovine colostrum and serum samples (Weaver et al., 2000; Godden, 2008; Deelen et al., 2014). Radial immunodiffusion is laboratory-based and takes, on average, 24 hours; therefore, it is not practical for on-farm monitoring of IgG concentrations in either colostrum or serum samples (MacFarlane et al., 2014). Brix Refractometry, which measures the solids in a colostrum sample prior to feeding, provides an efficient and accurate alternative for testing colostrum quality in a farm setting (Quigley et al., 2013). The aforementioned colostrum quality threshold of 50 g IgG per litre of colostrum corresponds with a Brix refractometer reading of 22% (Bielmann et al., 2010). Nevertheless, Conneely et al. (2013) found that the mean colostral IgG concentration on Irish dairy farms was approximately 112 g/L; this is substantially higher than the recommended quality threshold of 50 g/L IgG (McGuirk and Collins, 2004).

The calf may be blood sampled at 24 hours of age to ensure they have achieved ATP (Elsohaby et al., 2019). Passive transfer is said to be achieved when the calf has a serum IgG > 10 g/L at 24 hours old (Weaver et al., 2000; Godden, 2008). However, recent research from Godden et al. (2019) recommends a proposed consensus standard in which IgG levels are divided into categories, namely excellent (IgG > 25.0 g/L), good (IgG 18.0-

24.9 g/L), fair (IgG 10.0-17.9 g/L) and poor (IgG <10.0 g/L). Less than 10% of calves should occupy the poor serum IgG category. Therefore, the objective of the proposed consensus standard is to improve calf health within the US dairy industry (Godden et al., 2019).

2.1.1.5 Transition Milk

Transition milk is the milk produced by the cow in the second to the sixth milking after calving (Godden, 2008; Conneely et al., 2014; O'Callaghan et al., 2020). The quality of transition milk is not as good as that of colostrum (Stott et al., 1981), and although the calf can no longer absorb proteins across through their gut 24 hours after calving, there are health (Conneely et al., 2014) and growth benefits (van Soest et al., 2020) associated with feeding transition milk. This is because of localized immunity in the calf gut (Berge et al., 2009). Gut health is vital for the calf (Malmuthuge and Guan, 2017), therefore feeding transition milk, which is abundant with oligosaccharides (Fischer-Tlustos et al., 2020), may improve calf health (Berge et al., 2009; Conneely et al., 2014) and pre-weaning mortality (Pyo et al., 2018). Enteritis and diarrhoea are the most common cause of morbidity in Irish dairy calves (AFBI and DAFM, 2017); feeding transition milk could improve calf health. In Ireland, the recommended milk-feeding rate for calves is a volume equivalent to 15% of BW per day (e.g., 6L per day for a 40 kg calf; Conneely et al., 2014). The practice of feeding transition milk to calves in Ireland is widespread; 73% of respondents in a survey of pasture-based dairy farmers revealed that they fed at least five feeds of transition milk (Conneely et al., 2014). There are also economic benefits to feeding transition milk; it supplies the calf with the essential nutrients, and it is cost-free because it is otherwise unsalable for human consumption (Foley and Otterby, 1978).

2.1.2 Milk-Feeding Strategies

The objective of the pre-weaning period is to maximize BW gain through the consumption of milk (Morrison et al., 2009a), develop the rumen by providing concentrates and roughage (Dias et al., 2017), and minimize health issues (Morrison et al., 2009b). At birth, the rumen of a calf is non-functional, and therefore, a liquid-based diet (i.e., either WM or MR) should be offered throughout the pre-weaning period (Khan et al., 2011). Whether to feed WM or MR is generally a personal choice for each farmer; however, factors such as cost (Godden et al., 2005), convenience, and disease (McAloon et al., 2017) must be considered.

2.1.2.1 Whole Milk

The quality of nonsalable WM can be highly variable (Moore et al., 2009); therefore, WM is often pasteurized prior to feeding to calves (Godden et al., 2005). The feeding of unpasteurized WM is common on Irish dairy farms; however, it was particularly widespread during the milk quota era; Cummins et al. (2016) and Barry et al. (2019) found that > 50% of farmers surveyed fed unpasteurized WM to their calves. This is consistent with a Canadian survey in which 36.8% of farmers cited using milk produced over the available quota as the reason for feeding unpasteurized WM (Vasseur et al., 2010). There are disadvantages to feeding unpasteurized WM to calves, such that if there are antibiotic residues present in the milk, it can contribute to the development of antimicrobial resistance (Maynou et al., 2017). Nevertheless, the fat content of WM is higher than that of MR, and as such, calves fed WM may have improved BW gain and higher weaning weights (Godden et al., 2005).

2.1.2.2 Milk Replacer

Although the use of MR is commonplace in calf rearing operations in the United States (USDA, 2011; Urie et al., 2018), it does not have the same recognition in pasture-based rearing systems such as that in Ireland. This may be because milk quotas, which were in place until 2015, have impeded MR usage. In a 2013 survey of Irish dairy farmers, less than 20% of calves were fed exclusively MR (Cummins et al., 2016). By 2019, this figure had increased to 69% (A Sinnott 2021, personal communication, 6 August), thus indicating that quota abolition may have favoured the use of MR. Nevertheless, MR feeding to calves is most cost-effective when milk price is high (James and Scott, 2016).

Protein is essential for growth (NRC, 2001), and as such, it is one of the most essential ingredients in a MR (Erickson et al., 1989). Milk replacers typically contain 23-26% CP. Increasing the CP content (>25%) of MR may linearly increase daily BW gain without changing feeding rate (Blome et al., 2003; Davis Rincker et al., 2011). Approximately 67% of Irish dairy farmers fed MR that contained ≥25% CP (A Sinnott 2021, personal communication, 6 August). Pre-weaning MR intake may also influence the long-term performance of the heifer whereby increasing the CP content of MR has the potential to reduce AFC by 27.5 days (Raeth-knight et al., 2009) and increase first lactation milk production (Drackley et al., 2008) relative to conventional MR feeding programs. However, others have found no advantages in terms of BW (Morrison et al., 2012), fertility, and milk production performance (Morrison et al., 2009a). Similarly, the calf's diet may be restricted by feeding MR with a lower CP concentration, for example, 20-22% (Bartlett et al., 2006). This is generally to increase the consumption of solid feed.

Another critical aspect of a feeding program is the protein source in MR. Protein sources can be either milk or vegetable proteins (Teagasc, 2017). Although vegetable protein MR, such as soy, are a cost-effective alternative (Davis and Drackley, 1998), they may impede BW gain, as the digestion of proteins from alternative sources is suboptimal (Moran, 2012), particularly in the first three to four weeks (AHI, 2021). Therefore, milk-derived proteins, such as whey, are the preferred source of protein in MR, particularly in the first weeks of life as they supply the calf with ample nutrients for growth (NRC, 2001).

2.1.2.3 Volume and Reconstitution

Early research advocates feeding approximately 10% of BW in MR or WM (Kertz et al., 1979; Jasper and Weary, 2002). However, although restricted MR feeding programs (feeding rate of 8-10% of bodyweight) promoted the intake of concentrates and roughage (Kertz et al., 1979; Jasper and Weary, 2002; Khan et al., 2011), this feeding rate merely satisfies maintenance growth rates of the calf (NRC, 2001; Drackley, 2007). The research undertaken by Davis Rincker et al. (2011), Bazeley et al. (2016), and Johnson et al. (2017), focused on restricting MR intake and found ADG in the pre-weaning period to be 0.44 kg/day, 0.48 kg/day, and 0.12 kg/day, respectively. Target growth rates of 0.75 kg/day are required to ensure heifers are well-grown throughout the rearing period. Therefore, there has been a renewed interest of late in intensive MR feeding programs, whereby the calf is fed at a rate of 15-20% bodyweight, with the aim of increasing BW gains early in life to promote a heavier calf at weaning (Bartlett et al., 2006; Hengst et al., 2012; MacPherson et al., 2016). Increasing the MR allowance has advantages that persist beyond weaning; calves fed intensively in the pre-weaning period calved approximately 14 days earlier (Davis Rincker et al., 2011).

As a result of the substantial increases in BW gains, there has also been a renewed interest in ad libitum MR feeding. A study showed that ad libitum fed calves consumed 89% more MR than conventionally fed calves, and as a result, gained approximately 63% more weight in the pre-weaning period (Jasper and Weary, 2002). Furthermore, average daily gains of up to 1 kg/day are achievable in ad libitum milk-feeding programs (Khan et al., 2011). However, although there may be negative associations between ad libitum MR feeding and pre-weaning concentrate intake, post-weaning concentrate intake was not depressed by feeding unlimited amounts of MR in the pre-weaning period (Appleby et al., 2001; Jasper and Weary, 2002; Schäff et al., 2016). The early weight advantage incurred by the ad libitum fed calves compensated for the reduction in concentrate intake (Jasper and Weary, 2002). High growth rates in early life are beneficial to the future productivity of the calf, such that pre-weaning ADG accounts for 22% of the variation in first lactation milk yield (Soberon et al., 2012a).

Although recommended reconstitution rates differ depending on the MR manufacturer, the consistency of MR can also be altered by increasing the reconstitution rate to achieve higher growth rates while keeping the feeding rate constant (Cowles et al., 2006). This provides an early weight advantage; however, it may not persist long term (Morrison et al., 2012). The consistency of MR may also be adjusted in order to restrict MR intake such that the reconstitution rate may be reduced to 12.5% solids (Cowles et al., 2006). This may be used as a tool to increase solid feed intake and thus ensure a smooth transition during weaning (Byrne et al., 2017).

2.1.3 Concentrate and Roughage Feeding

Although milk feeding is fundamental, pre-weaning solid feed intake is also essential for rumen development. Volatile fatty acids are produced from the fermentation of concentrates, and roughage help to stimulate rumination; therefore, the inclusion of solid feeds such as concentrate, straw, and hay are essential in all milk-feeding systems (Anderson et al., 1987; NRC, 2001). Offering solid feed pre-weaning can also influence calf welfare by reducing the stress experienced during the weaning process (Khan et al., 2011).

2.1.3.1 Concentrate

Although concentrate consumption in the first three weeks of life is negligible (Kertz et al., 1979; Lorenz et al., 2011), it is vital that concentrates be offered, as there are benefits in terms of rumen development (Lorenz et al., 2011). Concentrates have high levels of fermentable carbohydrates that promote the production of the volatile fatty acid butyrate; feeding concentrates is, therefore, desirable for differentiation of the rumen epithelium into rumen papillae (Sander et al., 1959; Akins et al., 2016). Cereal grains form the basis of the energy component of the concentrate; corn and wheat-based concentrate result in the accumulation of greater concentrations of ruminal butyrate in calves relative to barley and oat-based concentrates. Calves offered corn and wheat-based concentrates also had increased solid feed consumption, more-functional papillae, and consequentially more-functional rumens (Khan et al., 2008). The protein content of the concentrate is important; a CP content of 18-20% is desirable to maximize intake (NRC, 2001). While increasing the protein content of concentrate may seem desirable to supply the calf with adequate nutrients for muscle growth (NRC, 2001), Drackley (2008) found no merit in increasing the CP content from 18 to 22%. Increasing the CP content of concentrate may contribute to environmental nitrogen excretion (Sinclair et al., 2014) and should be avoided. The stage of life at which concentrates are offered is also critical. Although the quantities consumed in the first weeks of life are insignificant, the provision of concentrates is essential to enhance ruminal digestion development (Lorenz et al., 2011). In a survey of Canadian dairy farmers, concentrates were generally offered in the first seven days of life (Vasseur et al., 2010). This was consistent with a survey of Irish dairy farmers whereby 75% of farmers surveyed provided their calves with concentrates in the first week of life (Cummins et al., 2016). Finally, the quantity of concentrates offered will also influence performance (Leaver, 1973), and as such, concentrate consumption is often used as an indicator that calves are ready to be weaned. Although it has been suggested that calves are consuming ≥1 kg DM/day concentrates prior to weaning (Lorenz et al., 2011), in a survey of Canadian dairy farmers, when concentrates were offered ad libitum, calves had a median concentrate consumption of 2 kg DM/day concentrates. This was consistent with Cummins et al. (2016), whereby 67% of survey respondents targeted a concentrate intake of ≥2 kg DM/day concentrates at weaning.

2.1.3.2 Hay and Straw

There are conflicting opinions on the provision of forages to the pre-weaned calf. Some research discourages forage feeding because the physical size of the rumen is limited, and the accumulation of a large volume of undigested material in the rumen has the potential to reduce concentrate intakes (Stobo et al., 1966). The inclusion of forage in the diet may also be detrimental to FCE and ADG in the lead-up to weaning (Hill et al., 2008). Nevertheless, access to texturized forages may improve reticulorumen growth and consequentially enhance feed intake and efficiency (Coverdale et al., 2004; Khan et al., 2011; Montoro et al., 2013). Provision of forage in early life may also have positive associations with forage consumption in later life when heifers are offered a high forage diet (Khan et al., 2012). The type of forage offered is also necessary; for example, the consumption of barley and oat-based forages has been found to stimulate concentrate intake and BW gain from two weeks old (Castells et al., 2012).

Furthermore, Phillips (2004) discovered that calves offered a straw mixture ate more forage and concentrate than those offered hay; however, the straw had been treated with molasses and syrup; therefore, palatability may be responsible for increased intake. A survey of Irish dairy farmers found that 40% of farmers surveyed offered a combination of forages to their pre-weaned calves. However, only 52% of these provided forage to calves in the first week of life (Cummins et al., 2016). The provision of forage is essential, as it has been associated with increased concentrate consumption (Castells et al., 2012). The physical size of forage particles was also important; chopped hay improved dry matter intake and nutrient digestibility relative to ground hay (Coverdale et al., 2004; Montoro et al., 2013). Increased FCE and volatile fatty acid production, as a result of forage provision, were in response to an improved rumen environment (Coverdale et al., 2004; Castells et al., 2013).

2.1.3.3 Water

Water is also an essential ingredient for rumen development, and so the Department of Agriculture, Fisheries and Food (2020) recommends the provision of water to calves from birth. Although the water intake of calves before weaning is negligible (Hepola et al., 2008), there are positive associations between water and concentrate intake of the preweaned calf (Kertz et al., 1984). Moreover, providing calves with water may also increase BW gains (Kertz et al., 1984). Water goes directly into the rumen (Govil et al., 2017) and creates an ideal environment for fermentation by rumen bacteria, therefore, increase nutrient availability (Wickramasinghe et al., 2019). Therefore, the provision of water to calves from birth is crucial.

2.2 Weaning

The objective on many commercial farms is to wean calves from liquid to solid feed as soon as possible to reduce the costs associated with an extended milk-feeding period (Boulton et al., 2017; Hawkins et al., 2019). A calf can be weaned based on weight (Gorrill, 1964b), age (Kehoe et al., 2007), or concentrate consumption (Roth et al., 2009; Bennetton et al., 2019). Nevertheless, nutrition in the pre-weaning period is crucial because it initiates rumen development so that the calf can digest an exclusively solid feed diet at weaning. However, regardless of the criteria used to wean calves, a gradual reduction in the milk allowance fed to the calf is preferable, as it will facilitate a smooth transition from liquid to solid feed (Khan et al., 2015).

2.2.1 Weaning by Weight

It was traditionally recommended that calves be weaned by BW so that they would be at similar stages of digestive development (Bell, 1958; Gorrill, 1964a). However, the weight at which calves were weaned was significant; Gorrill (1964b) concluded that lighter weaning weights (46 kg) resulted in a growth depression that persisted until the calves were 180 days old. Weaning by weight is beneficial because it accounts for lighter calves at birth (Bell, 1958; Gorrill, 1964b). The criterion often used in the weaning of calves is that they should double their birth weight by weaning (Soberon et al., 2012b). In a survey of pasture-based dairy farmers, Cummins et al. (2016) found that 72% of respondents had a target weaning weight of 80-90 kg. However, although a high percentage of farmers reported weaning their heifers by weight, the author could not find a statistic for the proportion of Irish farmers that weigh their heifers. It must be assumed, therefore, that weighing is not routinely carried out.

2.2.2 Weaning by Age

Weight-for-age targets throughout the rearing period are expressed as a percentage of mature BW at a given age (Troccon, 1993). Therefore, it may be more consistent also to wean calves based on age. Up to 46% of heifer rearing costs are incurred in the milk-feeding period (Boulton et al., 2017); therefore, early weaning will influence the overall cost of rearing heifers. Recent research, however, has reported inadequate nutrient intakes and growth rates in six-week weaned calves compared to calves weaned at between eight (Eckert et al., 2015) and 12 weeks of age (de Passillé et al., 2011). Early-weaned calves increased their solid feed intake at the point of weaning; this indicates that milk is the feed of choice for the young calf, and as a result, if a calf is weaned early, the rumen may not be sufficiently developed to digest large quantities of solid feed (de Passillé et al., 2011, Eckert et al., 2015). Later-weaned calves increased their concentrate intake before weaning, despite also consuming large volumes of milk. Therefore, later-weaned calves had higher solid feed intakes before weaning, and so avoided a depression in weight gain post-weaning (de Passillé et al., 2011). In a 2016 survey of pasture-based Irish dairy farmers, 51% of respondents weaned calves at an average of nine to 11 weeks (Cummins, 2016). This figure was slightly lower in the United States and Canada, where the average weaning age was seven (Vasseur et al., 2010) and nine (USDA, 2014) weeks, respectively.

2.2.3 Weaning by Concentrate Consumption

Research shows that weaning a calf according to their ability to consume a specific amount of concentrate is preferable to weaning based on age (Roth et al., 2009; Nejad et al., 2013) and weight (Soberon et al., 2012a). A study by Quigley et al. (1995) found that when the weaning criterion was to consume ≥ 454 g/day for two consecutive days, the average weaning age was 40 days. More recent research advocates gradually weaning calves when they consume ≥ 700 g concentrate per day for several consecutive days (Roth et al., 2009; Lorenz et al., 2011; Cummins et al., 2016; Byrne et al., 2017). However, a study in which calves were weaned when they consumed 500, 650, and 800 g/day of concentrates for three days respectively, reported that although calves fed 500 g/day of concentrates were weaned earlier, differences in the BW of calves when the trial concluded were negligible (Nejad et al. 2013). Calves weaned based on concentrate intake were weaned on average eight days earlier than calves weaned in a conventional milk-feeding system (Roth et al., 2009). There is variation in the age at which calves begin to consume concentrates (de Passillé and Rushen, 2016; Neave et al., 2018); therefore, the concentrate-dependent method of weaning ensures the nutritional requirements of each calf are met (Roth et al., 2009).

2.2.4 Abrupt Compared to Gradual Weaning

Weaning the calf from milk to solid feed can be either abrupt or gradual. Abruptly weaned calves experience a depression in weight gain after weaning because they have not had time to adapt to an exclusively solid feed diet before milk is withdrawn (Khan et al., 2007, Roth et al., 2009; Sweeny et al., 2010; Steele et al., 2017). In a study carried out by Sweeney et al. (2010), it was reported that although calves had an average daily weight gain of 1 kg/d prior to weaning, they lost weight in the days after they were abruptly weaned. Feeding elevated milk levels will discourage the consumption of solid feed, and so when milk is removed abruptly, intake of roughage and concentrate will be poor as the calf adjusts to their new diet (Sweeney et al., 2010). As such, abrupt weaning may be detrimental to gastrointestinal tract development (Steele et al., 2017).

Reducing the volume of milk or MR fed to calves in an effort to increase the proportion of solid feed in their diet is also known as gradual weaning, and it facilitates a smooth transition from liquid to solid feed (Khan et al., 2015). Gradual weaning can be carried out by slowly reducing the quantity of milk offered to the calf (Miller-Cushon et al., 2013) or by diluting the milk with water (Khan et al., 2007), both of which encourage DMI and consequently, BW gain (Khan et al., 2007, Eckert et al., 2015, Rosenberger et al., 2017). The calf becomes accustomed to reduced milk allowance before weaning and can increase their concentrate intake accordingly; gradually-weaned calves can consume up to 1.8 times more concentrates than those that were abruptly weaned (Steele et al., 2017). A study by Sweeney et al. (2010) found that the optimum duration for weaning was 10 days; this resulted in the highest weight gains both during and after weaning.

2.3 Post-Weaning Heifer Management

The objective of heifer management in the post-weaning period is to ensure that BW gain is optimized so that the heifer has achieved puberty before the commencement of the breeding season (Day and Nogueira, 2013). In confinement systems of heifer rearing, heifers are generally offered a consistently high-quality feed because precision nutrition is utilized to ensure the heifers are supplied with the exact nutrients necessary to grow (Zanton and Heinrichs, 2008b). However, post-weaning heifer management is entirely different in pasture-based heifer rearing systems; it generally involves allocating pasture (Patterson et al., 2018) and supplementing with concentrates if either grass growth or quality is poor (Creighton et al., 2011).

2.3.1 Pasture-Based Heifer Management

Pasture-based heifer management is comprised of two critical periods; the grazing season and the winter housing period. The practice of grazing from early spring to late autumn and offering conserved forages indoors during the winter takes advantage of the seasonality of grass production in Ireland (Drennan et al. 2005) and ensures heifers are sheltered during the winter when weather conditions may be poor (O’Driscoll et al., 2009).

2.3.1.1 Grazing Season

With a cost ratio of grazed grass to concentrates of 1:2.4 (Finneran et al., 2010), grass is the cheapest feed source for young ruminants. Time spent grazing is also one of the most significant determinants of heifer rearing costs (Boulton et al., 2017); each extra percentage increase of time spent at grass is associated with a £13.29 (€15.50) decrease in heifer rearing costs (Figure 2.1). Grass is also a complete feed; an exclusively pasture-based diet can support ADG of up to 0.82 kg/heifer/day (Patterson et al., 2018).

Despite grass being the predominant feed for pasture-based heifers, there has been very little research on the grassland management of heifers. Correct management of pasture is essential as it influences both the chemical composition of the sward and animal performance thereafter (Kennedy et al., 2007 McEvoy et al., 2009). Traditionally, a leader-follower system of grazing management was recommended whereby the younger animals would graze ahead of the older animals to ensure they had access to good quality grass with minimal disease burden (French et al., 2001). However, since milk quotas were abolished, young stock are often reared on an out-farm to maximize profitability on the milking platform (Shalloo et al., 2012). Rotational grazing systems have since become more common. Pasture allowance (Patterson et al., 2018) and pre-grazing herbage mass (Wims et al., 2010) are the main determinants of DMI, and consequently, BW gain during grazing. Calves are selective grazers; therefore, young leafy grass is most palatable and digestible (Beecher et al., 2015). In a survey of Irish pasture-based dairy farmers, 95% of respondents offered calves light (<1200) pre-grazing herbage mass swards (Cummins et al., 2016), which will improve grass quality and BW gain, while grazing high pre-grazing herbage mass swards (2200 kg DM/ha; Wims et al., 2010) will reduce feeding value of grass and depress DMI (O'Donovan and Delaby, 2008). However, some studies have found no associations between DMI and pre-grazing herbage mass (Owens et al., 2008;

Curran et al., 2010). Curran et al. (2010) concluded that pasture allowance had a greater impact on DMI than pre-grazing herbage mass.

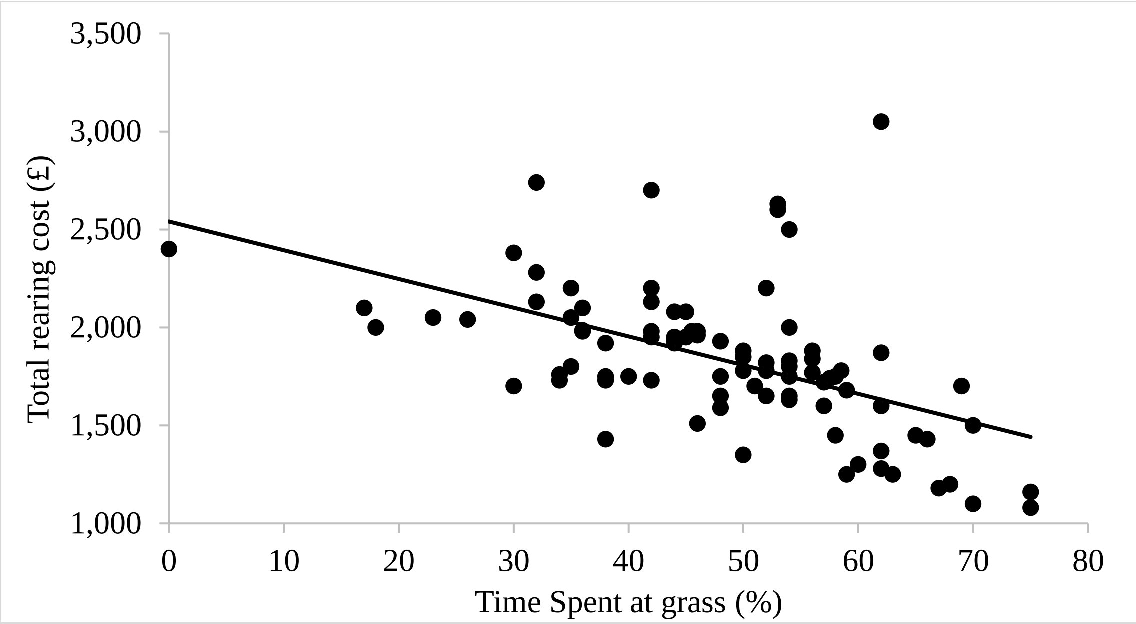


Figure 2.1: The relationship between the total cost of rearing and the time spent grazing. Adapted from Boulton et al. (2017); each symbol represents the data from one farm.

Although increasing pasture allowance is generally associated with an increase in DMI and consequently, ADG as pasture allowance increases, pasture utilization will be decreased, which will, in turn, lead to a suboptimal herbage quality in subsequent grazing rotations (Figure 2.2; Patterson et al., 2018). Pasture allowances that will optimize both animal performance and grass quality are required to support efficient and sustainable pasture-based systems (Pollock et al., 2020). Pasture allowances for lactating dairy cows are based on the kg of DM required to support good milk production (Curran et al., 2010). The objective of pasture allowances for dairy heifers would be to support BW gain. Therefore, as the daily DMI requirement of a pasture-based heifer is effectively unknown, pasture allowance is often expressed as a percentage of BW. Patterson et al. (2018) investigated pasture allowances of 1.8, 2.4, or 3.0% of bodyweight for dairy heifers and found an allowance of 2.4% of dry matter per kg BW to be the perfect compromise between animal performance and grass quality. Grass utilization decreased by 24%, and BW gain increased by 0.19 kg/day as pasture allowance increased from 1.8 to 3.0% (Patterson et al., 2018). This is consistent with Curran et al. (2010), who reported lactating dairy cows on high pasture allowances to have significantly higher BW. There is also much deliberation on the frequency of pasture allocation. Many studies report that increasing the frequency of pasture allowance will benefit DMI and consequently, milk production performance (Fulkerson et al., 2005; Abrahamse et al., 2008; McEvoy et al., 2009), which is conceivable because >70% of daily intake of pasture occurs within the first 3-4.5 hours of grazing (Trevaskis et al., 2004). Nevertheless, animals must adjust their grazing behaviour in response to an increase in the frequency of pasture allowance (Kennedy et al., 2011; Verdon et al., 2018), which may negatively influence the digestive process. Pollock et al. (2020) investigated the frequency of pasture allocation and found that 36-hour allocations were most suitable for primiparous animals. Different pasture allowances may also be achieved by targeting different post-grazing sward heights (Maher et al., 2003; Kennedy et al., 2006; McEvoy et al., 2009). At low post-grazing sward heights (3.2-3.8 cm; Kennedy et al., 2006), grass quality is a barrier to DMI (Wade, 1991) and, as such, ADG. Similar to increasing pasture allowance, higher post-grazing sward heights (4.7-5.7 cm) resulted in reduced sward utilization (Kennedy et al., 2006).

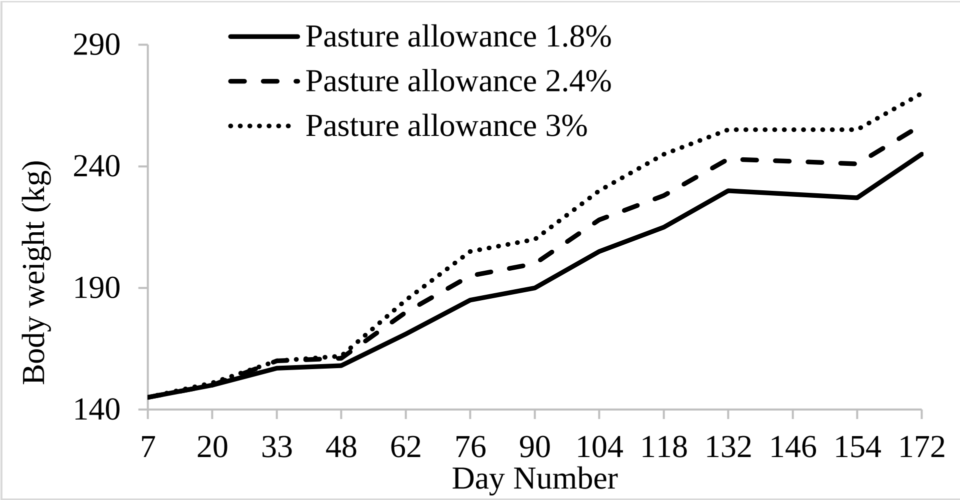


Figure 2.2: The effect of pasture allowance on the body weight of dairy heifers. Adapted from Patterson et al. (2018).

In the event of adverse weather conditions, grass quality may be variable, and concentrate supplementation may be necessary to subsidize BW gain (Kennedy et al., 2008) and milk production (McKay et al., 2019). Vendramini et al. (2007) reported higher ADG for calves offered concentrate supplementation than those offered pasture only; increasing supplementation levels from 0% to 2% BW increased ADG from 0.42 to 0.65 kg/day. This practice is beneficial to ensure heifers attain weight-for-age targets (Troccon, 1993); however, concentrate supplementation is expensive (Finneran et al., 2010) and so is associated with a reduction in farm profitability (McCarthy et al., 2007; Hanrahan et al., 2017).

2.3.1.2 Over-Winter Management

The seasonality of a pasture-based dairy farm means that the supply of grass in the spring and autumn often exceeds that of the demand (Wingler and Hennessy, 2016). Surplus grass grown during the summer season is generally conserved as silage, which will be fed during winter when weather conditions and grass growth are poor (Finneran et al., 2012). Although feeding grass silage is more expensive than that of grazed grass, it is more cost-effective than feeding concentrate; the cost ratio of feeding grass compared to that of silage and concentrate is 1:1.8:2.4 (Finneran et al., 2010). Silage quality is commonly of suboptimal quality compared to grass (Kavanagh, 2016), and as such, it is expected that BW gain during the over-winter period will be inferior. However, this may also be because heifers undergo a period of dietary acclimatization (O'Driscoll et al., 2009). However, very low ADG during the winter period may be detrimental to lactation (Le Cozler et al., 2010) and fertility performance (Heinrichs, 1996). In Ireland, heifers are commonly housed for the duration of the over-winter period (O'Connell et al., 1993). There is a capital cost of approximately €1,000 per animal associated with housing stock during the winter period (Teagasc, 2016a).

Alternatively, heifers may be reared outdoors over winter to reduce costs (Atkins et al., 2020). Typical out-wintering of heifers involves grazing fodder crops such as kale or fodder beet in situ (Edwards et al., 2017; Atkins et al., 2020). Kale and fodder beet are incredibly high in quality, and thus a smaller allowance is required (Atkins et al. 2018). However, the aforementioned fodder crops also have a low concentration of neutral-detergent fibre; therefore, supplementation with a forage crop, i.e., silage, straw, or hay, may be required to prevent acidosis (Keogh et al., 2009). Although it is expensive to harvest and feed out to heifers, fodder beet grazed in situ is considerably cheaper than producing and feeding grass silage (Finneran et al., 2010). However, as with any forage crop grazed in situ, the concomitant muddy soil may be perceived as an animal welfare issue (Atkins et al., 2020). Nevertheless, previous research reports respectable ADG

(Kennedy et al., 2013; Atkins et al., 2020) without detriment to first lactation milk production (Atkins et al., 2015). Heifers can adapt their behaviour to climatic conditions to reduce energy expenditure (Redbo et al., 2001). As such, out-wintering heifers is considered a viable and cost-effect alternative as it facilitates expansion without high capital expenditure on winter housing (Atkins et al., 2015; Barnes et al., 2013).

2.3.2 Confinement

In confinement dairy systems, heifers are generally housed year-round and offered a TMR diet of consistently good quality (McDougall, 2006). Indoor rearing facilitates feeding a nutritionally balanced diet to optimize production (i.e., BW gain), and it has benefits in terms of animal welfare because heifers are protected from extreme weather conditions (Schütz et al., 2010). In 2014, 86.9% of heifers in the United States were reared in confinement (USDA, 2014). Year-round housing is also becoming more prevalent in Europe; in the Netherlands, 29% of dairy cows are indoor-housed (CBS, 2019). The cost of rearing a heifer in confinement was $583 (€496) more expensive than that of rearing a pasture-based heifer (Hawkins et al., 2020), with housing accounting for 17% of heifer rearing costs (Akins et al., 2017). However, intensively-reared heifers have a higher capacity for milk production in the first lactation (Soberon et al., 2012b; Van Amburgh et al., 2014), and as such, are more profitable in the long term (Overton and Dhuyvetter, 2017).

2.3.2.1 Precision Nutrition

Precision feeding improves the efficiency of nutrient utilization without adverse effects on the future performance of the animal (Van Amburgh et al., 2015). Precision nutrition feeding programs involve feeding TMR rations high in protein but without enough energy to cause the animal to become over-fat (Van Amburgh et al., 2009; Soberon et al., 2012b). Rations are formulated to different nutrient specifications based on the production potential of the heifer, their age and stage of development, energy expenditure, the environment, and characteristics of the available ration (González et al., 2018). Environmental stress as a result of climate variation may alter the energy requirements of animals (White and Capper, 2014); therefore, formulating diets on a seasonal basis may improve the efficiency of nutrient utilization. Corn and soybean meal are the predominant sources of energy and protein, while corn silage is the predominant source of forage (Zanton and Heinrichs, 2008a). An example of precision nutrition feeding is the Cornell Net Carbohydrate and Protein System, established in 1992 and 1993 (Fox et al., 1992; Russell et al., 1992; O’Connor et al., 1993) to formulate feed for animals. The system is updated regularly to ensure that the model's capacity to formulate diets remains effective (Van Amburgh et al., 2015).

Another example is the INRA feeding system for ruminants (INRA, 2010), which predicts the supply of nutrients in feed, an animal's requirements, and the expected animal response to diets. These feeding systems are becoming ever more critical because the overfeeding of nutrients can result in excessive excretion of nutrients into the environment (NRC, 2001). Manipulating the CP and phosphorus in heifer ration may reduce harmful emissions (Frank and Swenson, 2002; INRA, 2010).

2.4 Dry Matter Intake

2.4.1 Factors Affecting Dry Matter Intake

Dry matter intake is a key determinant of BW, the proper management of which is essential to ensure the success of a heifer rearing enterprise. Hoffman et al. (2008) reported the DMI of Holstein heifers reared in confinement to range from 4.73 to 12.26 kg/day throughout the rearing period. However, there has been very little research undertaken on the DMI of pasture-based dairy heifers; this may be because there is considerable variation in DMI due to fluctuations in grass growth and quality throughout the grazing season (Litherland et al. 2002); however, it may also be because DMI is difficult and costly to measure (Seymour et al., 2019). The lack of research on heifer DMI limits both the optimization of heifer BW and the creation of suitable grassland management strategies. The following section will review in more detail the factors that affect DMI in dairy heifers, the methodologies employed to determine DMI, and the creation of DMI prediction equations.

2.4.1.1 Body Weight

Previous research has reported a strong relationship between DMI and heifer BW (Quigley et al., 1986a; 1986b; Stakelum and Connolly, 1987); however, the relationship may not be as straightforward for a pasture-based heifer DMI due to seasonal variation in grass growth and quality (Hennessy et al., 2020) and consequently, heifer BW (Handcock et al., 2021). In general, as heifer BW increases, so too does DMI (Quigley et al., 1986a); this is corroborated by the fact that heifer DMI is often expressed as a percentage of BW. Heifer DMI as a percent of BW decreases as BW increases (NRC, 2001; Hoffman, 2013).

This suggests that the intake capacity of a heifer is highest in early life. A study by Stallings et al. (1985) found the DMI of growing heifers to be 3.3% of BW; by the time these animals had completed their first lactation, DMI as a percentage of BW was 2%, this substantiates the claim that intake capacity is higher in early life. A high intake capacity in pasture-based rearing systems is desirable as it indicates that the animals are capable of being good grazers (Delaby et al., 2020).

2.4.1.2 Feed Composition

Consistent with dairy cows (Kennedy et al., 2008; McEvoy et al., 2008), concentrate is the feed of choice for dairy heifers (DeVries et al., 2009), the consumption of which will significantly increase DMI. Diets containing a high proportion of concentrates are utilised with greater efficiency than those containing a high proportion of forages (Garrett, 1979; Zanton and Heinrichs, 2007). High concentrate diets also favour milk production performance (Zanton and Heinrichs, 2007). In confinement systems of heifer rearing, rations are generally fed at a rate of 2.2% of BW (Hawkins et al., 2020), supplying the animal with the exact amount of digestible nutrients for adequate growth without affecting future performance (Zanton and Heinrichs, 2007). In contrast, altering diet composition in pasture-based systems is generally achieved by grassland management strategies, such as varying stocking rates and DHA (Horan et al., 2004; Coffey et al., 2017) which will influence the quality of grass offered to the animals. Increasing the quantity of pasture offered to the animals is generally conducive to high DMI (McEvoy et al., 2008; Kennedy et al., 2009). In contrast, reducing the quantity of pasture offered to the animals will reduce the quality because, in grazing, animals selectively remove grass leaves in preference to stem (Van Dyne et al., 1980).

2.4.1.3 Breed

There are significant differences in the DMI of different breed groups (Prendiville et al., 2010). Although JE heifers spend a similar amount of time grazing to HF, they have a lower DMI (Prendiville et al., 2010). This may be because DMI is limited by the smaller body size of the JE (Rook et al., 2000; Prendiville et al., 2010). However, when DMI is expressed as a percentage of BW, JE heifers have a higher DMI than HF (Prendiville et al., 2010; Coffey et al., 2017). This is often termed intake capacity (Goddard and Grainger, 2004). The superior intake capacity of JE heifers may be because they have a larger digestive tract than HF (Beecher et al., 2014). This indicates that they have the capability to be good grazers and so are well suited to a pasture-based system (Prendiville et al., 2010; Delaby et al., 2020).

2.4.2 Determining Dry Matter Intake

Simple methods of DMI estimation, such as herbage disappeared, are readily available; however, this does not permit individual DMI estimation, which is advantageous in a research setting. Individual DMI estimation would facilitate a change to feeding animals the specific nutrients required for their production level (i.e., BW for heifers and milk production for lactating cows). However, the differences in how DMI is measured (Seymour et al., 2019) may ultimately result in different levels of accuracy.

2.4.2.1 Herbage Disappeared

Herbage disappeared is undoubtedly the simplest and most cost-effective method of measuring heifer DMI (Seymour et al., 2019). A rising plate meter is used to measure the pre-grazing herbage mass before grazing and the post-grazing herbage mass after grazing (O'Donovan et al., 2002). The difference between pre and post-grazing herbage mass is assumed the DMI of the animals grazing (Gregorini et al., 2009; Johnson et al., 2015; Alvarez-Hess et al., 2021). The herbage disappeared method is similar to weighing orts (i.e., weighing the quantity of feed offered and the quantity of feed refused), which is commonly practiced in confinement systems of rearing (Silva et al., 2018). However, the herbage disappeared method of DMI estimation may be unsuitable for a research setting as it is incapable of establishing individual heifer DMI (Seymour et al., 2019).

2.4.2.2 Marker Techniques

The DMI of pasture-based dairy heifers is generally determined using indigestible fecal markers such as *n*-alkanes (Mayes et al., 1986; Dillon and Stakelum, 1989), NDF (Marquez et al., 2017), and rumen-undegraded DM (Ferret et al., 1999). However, the *n*-alkane technique is most commonly used to determine DMI in pasture-based systems such as Ireland. The process involves dosing individual animals daily with an *n*-alkane bolus, performing individual fecal collections, and analysing both fecal samples for the dosed marker and grass samples for the naturally occurring marker (Wright et al., 2019; McGovern et al., 2021). Although this technique is highly accurate in measuring individual heifer DMI, it is incredibly labour-intensive. In addition to the cost of labour, the cost of producing the boluses and analysing samples mean that, although accurate, marker techniques are an expensive means of measuring DMI (Seymour et al., 2019).

2.4.2.3 Calan Gate

The Calan gate (Calan gates; American Calan Inc., Northwood, NH) system of measuring DMI involves the use of radio frequency identification tags to record when an individual animal enters the feed trough electronically. Feed dispensed into the feed bin is then weighed, and the difference in weight of feed upon exiting the feed bin is electronically recorded (Berry et al., 2014). The Calan gate system is limited because animals must be housed to achieve accurate results; as such, it is not suitable for use in grazing animals. Furthermore, although this system is beneficial because it facilitates the measurement of individual heifer DMI without impeding workflow or interrupting feeding behaviour on the farm (Halachmi et al., 1998; Shelley et al., 2016), the feed system requires a significant capital investment (Seymour et al., 2019).

2.4.3 Dry Matter Intake Prediction Equations

Measuring DMI using the aforementioned methods is regularly carried out in a research setting, and the resulting DMI is used in the creation of DMI prediction equations (Quigley et al., 1985; NRC, 2001). Such equations are beneficial because, in using them, commercial farmers can monitor the DMI of their animals. There are various equations available to predict the DMI of pasture-based dairy cows (O’Neill et al., 2013; Lahart et al., 2019), which is correlated with milk production, such that the level of feed offered may be increased to boost milk production performance (Roche, 2007a). There is a similar principle in pasture-based youngstock; however, DMI is instead used to support growth performance (NRC, 2001); a suboptimal DMI may mean that a heifer will fail to achieve the weight-for-age targets set out by Troccon (1993). Equations to predict the DMI of heifers reared in confinement include BW, the heifer's maintenance requirement (NRC, 2001), or the digestible nutrients in the diet (Quigley et al., 1986). Nevertheless, as the quality of grass before grazing is generally unknown, existing DMI prediction equations are not suitable for use on pasture-based heifers.

2.4.3.1 Feed Composition

Although Quigley et al. (1986a) delineated that BW and BW gain are correlated with DMI, the inclusion of digestible nutrients in the equation was found to increase its prediction accuracy. Dry matter intake prediction equations are widely utilized, under the guise of precision nutrition, in countries where heifers are housed year-round and offered a feed of consistent quality (NRC, 2001; Zanton and Heinrichs et al., 2008b; Hoffman et al., 2008). Heifer diets are designed to supply specific nutrient densities in precision nutrition regimes to ensure growth is optimized (NRC, 2001). As such, digestible nutrients in the diet are the focus of existing equations to predict the DMI of heifers reared in confinement (Quigley et al., 1986b). Equations commonly include dietary NDF, ADF, and CP (Quigley et al., 1986b). The equation created by NRC (2001) to predict the DMI of growing heifers, containing a proxy for BW and the net energy for heifer maintenance, is widely used in diet formulation.

2.4.3.2 Body Weight

The importance of BW in DMI prediction equations is indisputable, as is evidenced by its inclusion in prominent equations alongside digestible nutrients (Quigley et al., 1986b; NRC, 2001). Nevertheless, previously published equations tend to over or under-predict the DMI of light or heavy heifers (Hoffman et al., 2008). In pasture-based production systems, where the quality of grass is largely unknown prior to grazing, it is important that DMI prediction equations be based on a trait that is easily monitored by farmers. As such, an equation based exclusively on animal parameters is preferable to one based on dietary components. Furthermore, heifer DMI as a percentage of BW has been reported to decrease as BW increases (NRC, 2001; Hoffman and Kester, 2013); therefore, DMI prediction equations incorporating BW throughout the rearing period are preferable. However, previously published heifer DMI equations without dietary components are either sparse or have a significant error of prediction (Stallings et al., 1985).

2.5 Heifer Growth

Heifer growth throughout the rearing period is significant in terms of the attainment of puberty (Archbold et al., 2012), milk production potential and reproductive efficiency (Handcock et al., 2020). In confinement systems of heifer rearing, growth follows a linear pattern as heifers are offered feed of consistently good quality throughout the rearing period (NRC, 2001; Zanton and Heinrichs et al., 2008b; Hoffman et al., 2008). In pasture-based systems of heifer rearing, however, a linear growth trajectory is unattainable due to variation in grass growth and quality (Handcock et al., 2019a; Hennessy et al., 2020). Therefore, the monitoring of pasture-based heifer growth is even more important to ensure they have gained the BW necessary to achieve puberty prior to the breeding season (Archbold et al., 2012). Nevertheless, farm fragmentation (Hennessy et al., 2020) since the abolition of milk quotas is a barrier to the regular monitoring of pasture-based heifer growth (Hennessy et al., 2020). Common methods for monitoring heifer growth are weighing (Lukuyu, et al 2016), LBM (Heinrichs et al., 1992), or BCS (Edmonson et al., 1989).

2.5.1 Body Weight

Body weight, measured using an electronic scale, is the most widely used indicator of heifer growth (Lukuyu et al., 2016). Nevertheless, there is no available information on the proportion of Irish farmers that weigh their heifers, thus indicating that the uptake of technology is particularly low (Teagasc, 2016b). A similar pattern was observed in New Zealand, whereby less than 5% of heifers had a BW recorded prior to calving (McNaughton and Lopdell 2012). Body weight also differs with heifer rearing system; the growth pattern of pasture-based heifers is different from that of heifers reared in confinement (Handcock et al., 2021). Handcock et al. (2019a) observed the growth of pasture-based dairy heifers to be curvilinear, with the fastest growth observed from 3-5 and 12-20 months of age; this may be because there is seasonal variation in grass growth and quality (Hennessy et al., 2020). In Ireland, heifers are generally housed during the over-winter period with conserved forages as the predominant feedstuff (Kavanagh, 2016), while heifers in New Zealand are out-wintered on forage crops such as kale and fodder beet (Edwards et al. 2017; Atkins et al., 2020). Irrespective of over-winter management, pasture-based heifers undergo a period of dietary adjustment, which may explain the temporary deceleration in growth (Swatland, 1994; O'Driscoll et al., 2009). Body weight of heifers also differs with breed group; HF heifers are heavier than JE at all stages of growth (Enevoldsen and Kristensen, 1997; Handcock et al., 2019a).

2.5.2 Linear Body Measurements

In the absence of electronic weighing scales, LBM such as HG, WH, and BL (Lukuyu et al., 2016) may be used to monitor heifer growth. Heart girth is highly correlated with BW

(Heinrichs et al., 1992) and is, therefore, the most widely used LBM. It appears that length is more likely to be static than girth and height, thus signifying a different mechanism in the pattern of linear body growth compared with BW (Moallem et al., 2010). Linear body measurements vary with breed (Reis et al., 2008). This was expected due to the vast differences in BW and skeletal structure for mature HF and JE animals (Davis and Hathaway, 1956; Prendiville et al., 2011a). Linear measurements are a cheap alternative to monitoring BW using an electronic scale (Tebug et al., 2018).

2.5.3 Body Condition Score

Body condition score is another frequently used method to monitor heifer development based on fat cover over the lumbar and pelvic regions (Wildman et al., 1982). Body condition score is often assessed on a scale of 1-5 (Edmonson et al., 1989), where one indicates emaciation and five indicates obesity. It is widely accepted that a heifer should have a BCS of >2.5 at breeding to ensure reproductive success (Buckley et al., 2003, Mulligan et al., 2006; Archbold et al., 2012), a lower BCS may delay calving date and implicate reproduction thereafter (Archbold et al., 2012). A BCS of 3.0 at calving is desirable to minimize loss of condition in early lactation; over-conditioned cows may have excessive mobilization of body reserves (Pryce et al., 2001; Mulligan et al., 2006). Body condition score losses of >0.5 in early lactation have been negatively associated with subsequent reproductive performance (Britt, 1992; Buckley et al., 2003; Butler, 2005). Holstein-Friesian and JE animals differ in terms of body measurements and condition (Enevoldsen and Kristensen, 1997).

2.6 Weight-for-Age Targets

Body weight is used extensively to define the optimum body size of replacement dairy heifers (Archbold et al., 2012; Morrison et al., 2012). Setting weight-for-age targets for replacement heifers is an indicator of animal performance and facilitates the farmer to measure the growth performance of their herd against that of the national herd. Despite the evident differences in the way in which heifers under different systems of management are reared, the weight-for-age targets outlined by Troccon (1993) are used internationally. Weight-for-age targets are expressed as a percentage of mature BW (Roche et al., 2015). Therefore, knowledge of the mature BW of the herd is essential to ensure that heifers are not under or overgrown in relation to their weight-for-age target.

2.6.1 Mature Body Weight of the Herd

Mature BW is intrinsic to setting weight-for-age targets for dairy heifers. Mature BW cannot be determined for several years until skeletal, and muscle tissue growth has ceased (Fitzhugh & Taylor 1971). The herd average mature BW of the herd is commonly established by weighing a representative proportion of third, fourth, and fifth lactation animals in May/June when there was no effect of pregnancy on BW (AHI, 2016). In New Zealand, the mature BW is calculated by adding 500 kg to the average BW breeding value of a line of heifers (Handcock et al., 2019a). However, because there is considerable variation in BW breeding values within breed group, mature BW may be under or over-predicted; this may be detrimental to the attainment of weight-for-age targets. Mature BW differs with the genotype of the heifer (Akins, 2016). Holstein-Friesian heifers have a mature BW of between 550 kg and 580 kg (Archbold et al., 2012; Kennedy and Murphy, 2017), while JE heifers tend to have a lighter mature BW of 400 kg (Enevoldsen and

Kristensen, 1997; NRC, 2001). The environment in which the heifer is managed also influences the mature BW of the dairy heifer; heifers reared on pasture-based dairy farms may be lighter than those consuming TMR in confinement; this is due to the inconsistency of grass quality (Washburn et al., 2002; Roche et al., 2009). In a study carried out by Washburn et al. (2002), differences in BW could be attributed to both environment and breed; Holsteins in confinement were heavier (583 kg) than Holsteins at pasture (568 kg). Jerseys in confinement were also heavier (419 kg) than those at pasture (387 kg; Washburn et al., 2002).

2.6.2 Key Target Weights

Achieving targets of 30, 60, and 90% of mature BW at six, 15, and 24 months, respectively, will optimize the production potential of a heifer (Ettema and Santos, 2004; Wathes et al., 2008; Froidmont et al., 2013). Adhering to weight-for-age targets (Table 2.1; Troccon, 1993) will minimize excessive BW gain, which can be detrimental to the reproductive performance of the heifer (Archbold et al., 2012). Nevertheless, the aforementioned weight-for-age targets are calculated by linear interpolation, and as such, a linear growth trajectory is required (Troccon, 1993; Handcock et al., 2021). The growth of heifers reared at pasture is slightly more complex due to the seasonal calving systems often in place (Handcock et al., 2019a) and the annual variation in forage quality (O' Donovan et al., 2011). Weight-for-age targets are also crucial in a pasture-based heifer rearing system due to the seasonal breeding and calving imposed (Archbold et al., 2012). Ensuring that heifers are available for breeding at 15 months and thus calve down at 24 months is necessary so that calving coincides with grass growth, matching herd demand with grass supply (Archbold et al., 2012). The attainment of target BW at 15 months (breeding) is generally considered the most important objective as it benefits the pubertal status of the heifer (Troccon et al., 1993; Wathes et al., 2014). The attainment of the pre-breeding weight-for-age target has also been associated with longevity within the herd and with increased MS production (Martín et al., 2020). However, 44% of dairy heifers in New Zealand failed to achieve target weight at breeding, which may be a consequence of poor grass quality on pasture-based dairy farms (Roche et al., 2009; Handcock et al., 2016). Despite notable improvements in the attainment of weight-for-age targets in recent years, Handcock et al. (2016) found that 65% of heifers failed to achieve their pre-calving target BW.

Table 2.1: Body weight (BW) targets for growing heifers with different birth weights to achieve optimum body weight at first calving, adapted from Troccon (1993).

Age	Mature BW (kg)				
	450	500	550	600	650
Birth BW (kg)	30	35	40	45	45
84 days (weaning)	80 (0.60)	90 (0.65)	100 (0.71)	110 (0.77)	120 (0.89)
6 months	135 (0.57)	150 (0.63)	165 (0.68)	180 (0.73)	195 (0.78)
15 months (breeding)	270 (0.5)	300 (0.56)	330 (0.61)	360 (0.67)	390 (0.72)
24 months (calving)	405 (0.50)	450 (0.56)	495 (0.61)	540 (0.67)	585 (0.72)

2.6.3 Compensatory Growth

Traditionally, heifer rearing strategies that took advantage of compensatory growth were recommended to enhance mammary development and subsequent lactation performance (Park et al., 1998). Nutritionally directed compensatory growth regimes involve alternating a high-energy diet with a restricted-energy diet (Hoffman and Funk, 1992; Park et al., 1998). Such feeding regimes can increase first lactation milk production by up to 21% (Ford and Park, 2001). However, Kennedy et al. (2013) determined that the theory of compensatory growth should not be relied upon to attain weight-for-age targets.

2.7 Fertility

Fertility performance is of greater relative importance in a seasonal calving system (Veerkamp et al., 2002) due to seasonal breeding constraints (Berry et al., 2013). If a heifer does not gain the BW necessary to attain puberty and go in calf early in the breeding season, she will not be inseminated for a further 12 months; this increases the unproductive lifespan of the heifer (Patterson et al., 1992; Moran and Chamberlain, 2017). Good fertility performance is essential to maintain a compact calving pattern (Morton, 2010; Canadas et al., 2020), and a calving pattern is a key driver of farm profitability (Shalloo et al., 2014). Age at first calving, one of the key determinants of heifer rearing costs (Boulton et al., 2017), is a function of both heifer growth and fertility (Cooke et al., 2013). Reproduction accounts for between 2.5 and 4.4% of heifer rearing costs (Mohd Nor et al., 2015; Boulton et al., 2017); it is, therefore, important that weight-for-age targets be achieved throughout the rearing period (Troccon, 1993).

2.7.1 Factors Affecting Puberty

Heifers are said to reach puberty at a certain weight rather than age (Lammers et al., 1999; Le Cozler et al., 2008). This is consistent with Chelikani et al. (2003), who reported that puberty occurred when HF heifers weighed between 270 and 330 kg. Management in the pre (Khan et al., 2011) and post-weaning (Pereira et al., 2017; Le Cozler et al., 2019) period is capable of increasing BW and frame size of heifers (Pereira et al., 2017; Quintana et al., 2018), which are fundamental for the early attainment of puberty (Little and Kay, 1979; Le Cozler et al., 2008; Lohakare et al., 2012). However, while growth may be easily accelerated by diet formulation in confinement systems of heifer rearing (Zanton and Heinrichs, 2007; Erickson and Kalscheur, 2020), manipulation of the diet is more difficult in pasture-based heifer rearing systems. Heifers reared to achieve a linear growth trajectory reached puberty at a younger age than heifers reared to achieve a seasonal growth pattern (Handcock et al., 2021). As such, increasing BW gain in early life may be used as a tool to reduce the pubertal age of the heifer (Macdonald et al., 2005; Archbold et al., 2012). Achieving weight-for-age targets set out by Troccon (1993) will ensure heifers have achieved puberty and are available for breeding at 15 months, which is particularly important in systems that impose limited breeding periods (Patterson et al., 1992; MacMillan, 2012).

2.7.2 Key Fertility Performance Indicators

Infertility is the primary cause of culling on UK commercial herds (Brickell and Wathes, 2011); therefore, it is essential that heifers are reared to optimize fertility performance. Monitoring fertility performance by being cognizant of key performance indicators will contribute to reproductive efficiency. Key performance indicators are invaluable in the interpretation of farm productivity and profitability. The most desirable outcome of benchmarking is adopting better practices and the concomitant increase in farm profit. There are many indicators of reproductive efficiency, i.e., days from MSD to conception (Butler, 2014), submission rate (McDougall, 2006), pregnancy rate to first service (Evans et al., 2002), six-week calving rate (ICBF, 2020a), calving interval (ICBF, 2020a; Table 2.2) and AFC (Berry and Cromie, 2009).

Table 2.2: Fertility traits in the Irish national dairy herd. Adapted from ICBF (2020a).

Fertility performance indicator	Average	Top 10%	Bottom10%
Replacement rate (%)	20	18-22	N/A
Six-week calving rate (%)	65	85	36
Calving interval (days)	387	364	424
Heifers calved 22-26 months of age (%)	71	100	12

2.7.2.1 Days from Mating Start Date to Conception

Compact calving in a seasonal calving system demands excellent fertility, with most of the herd becoming pregnant during a defined breeding season, beginning in April or May (Berry et al., 2013). Although the date on which mating starts varies from farm to farm, the objective remains the same: to have at least 70% of the herd become pregnant in the first six weeks after MSD (Butler, 2014; Carty et al., 2020). Heavier heifers are more likely to go in calf earlier in the breeding season (Lesmeister et al., 1973; Patterson et al., 1989). Achieving weight-for-age targets (Troccon, 1993) is vital for reducing the interval from MSD to conception. Alternatively, the interval from the MSD to conception may be shortened using fixed-time AI protocols in seasonal-calving, pasture-based dairy production systems (Butler et al., 2012; Herlihy et al., 2011).

2.7.2.2 Submission Rate

Submission rate is defined as the proportion of all cows detected in estrus and submitted for AI, generally in the first 21 days of the breeding season (Mossa et al., 2012). Submission rate will influence the success of the subsequent calving season, such that a high submission rate will result in a compact calving pattern, which is desirable in a seasonal calving system (Butler et al., 2012). A submission rate of >80% in the first 21 days was traditionally targeted (McDougall, 2006); however, in more recent research, the target is to have >90% of animals submitted within the first 21 days of the breeding season (Butler, 2014; Canadas et al., 2020). In a study by Buckley et al. (2003), approximately 81% of animals were submitted within the first three weeks of the breeding season. Lower BCS in early lactation may be a barrier to achieving target 21-day submission rates (Buckley et al., 2003); therefore, feed management must be optimized to ensure reproductive success. The use of fixed-time AI protocols facilitate 100% submission rates; however, the performance of fixed-time AI is most favourable in cows that are >60 days in milk at the time (Herlihy et al., 2013).

2.7.2.3 Six-week Calving Rate

A key measure of reproductive performance in seasonal-calving dairy herds is the six-week (42-day) calving rate (McDougall, 2006), defined as the percentage of the herd that calve in the first six weeks of the calving season. The six-week calving rate is indicative of the spread of a calving pattern and is primarily influenced by the submission rate in the first 21 days of the breeding season and the conception rate to first service (Herlihy et al., 2013). The target is to have 90% of the herd calved within the first six weeks of the calving season (Teagasc, 2015). However, Ireland's national average six-week calving rate currently stands at 64% (ICBF, 2018), with only the top 5% of dairy farms currently achieving six-week calving rates of 89%. Nevertheless, high six-week calving rates (81-88%) were achievable in a controlled study of New Zealand dairy heifers. Increasing the six-week calving rate from 70% to 90% will increase annual farm profitability by €16,500 (Teagasc, 2015).

2.7.2.4 Pregnancy Rate to First Service

Pregnancy rate to the first service may also be used as an indicator of reproductive efficiency. If an animal does not become pregnant to her first service, it may increase the number of inseminations required to achieve pregnancy (Kim and Jeong, 2019). It costs on average €4.56/animal/year per 0.1 additional inseminations required (Shalloo et al., 2014), with the number of inseminations being negatively correlated with the likelihood of conception (Chebel et al., 2007), which may further contribute to the cost of infertility (Esslemont et al., 2018). Previous research has reported pregnancy to first service rates of between 42.3 and 55.6% (Evans et al., 2002; Berry et al., 2012; Kim and Jeong, 2019). Butler and Herlihy (2012) and Kim and Jeong (2019) observed a positive relationship between BCS and pregnancy to first service rates, this further highlights the importance of feed management in early lactation. Nevertheless, pregnancy to first service rates may also be improved by using a synchronization protocol as outlined by Kennedy et al. (2012), who reported pregnant to first service rates of up to 70% in pasture-based dairy heifers.

2.7.2.5 Calving Interval

Calving interval is the difference, in days, between successive calvings. A calving interval of 365 days is considered one of the most important indicators of reproductive efficiency as it reduces the number of non-productive days (ICBF, 2018). Calving intervals of 365 days are of particular importance in seasonal calving systems (McDougall, 2006) so that calving coincides with grass growth (Dillon et al., 1995), and as such, feed supply matches that of herd demand. Nevertheless, calving intervals in previous research are lagging behind target; Macdonald et al. (2005), Hanks and Kossaibati (2018), and

Eastham et al. (2018) reported calving intervals of 381, 388, and 401 days, respectively. Although Ireland's national average calving interval is 387 days, the top 5% of farms have calving intervals of 361 days, which is ahead of the target (ICBF, 2018). Improvements in the calving interval on Irish dairy farms are therefore possible. A shorter calving interval will significantly increase lifetime profit of the heifer (Do et al., 2013).

2.7.2.6 Age at First Calving

Age at first calving is one of the biggest determinants of heifer rearing costs (Boulton et al., 2017), with optimal economic returns associated with an AFC of between 22 and 24 months of age (Ettema and Santos, 2004; Hutchison et al., 2017). Nevertheless, AFC is also a function of the age at which puberty and conception occur (Van Amburgh et al., 1998). Achieving weight-for-age targets outlined by Troccon (1993) will optimize heifer growth in early life, ensure they have achieved puberty prior to the breeding season, and subsequently become pregnant early. In most pasture-based dairy systems, calving between 22 and 26 months is necessary to ensure a compact calving pattern (Shalloo et al., 2014) and ensure the competitive advantage of a pasture-based production system is optimized (Dillon et al., 1995; Finneran et al., 2010).

2.8 Calving at 24 Months

Calving at 24 months is one of the biggest influencers of heifer rearing costs (Figure 2.3; Boulton et al., 2017). It costs on average €1,545 (approximately 15-20% of production costs) to rear a heifer from birth until calving at 24 months (Shalloo et al., 2014). While an AFC of 24 months is generally targeted (Hanks and Kossaibati, 2018), in 2018, only 70% of heifers in Ireland calved between 22-26 months of age (ICBF, 2018). Calving between 22 and 26 months of age will increase lifetime milk production, longevity within the herd, and a lower replacement rate (ICBF, 2019). Nevertheless, reducing the AFC can reduce heifer rearing costs; a 4.3% reduction in heifer rearing costs was associated with a one-month reduction in AFC (from 25 to 24 months of age; Tozer and Heinrichs, 2001).

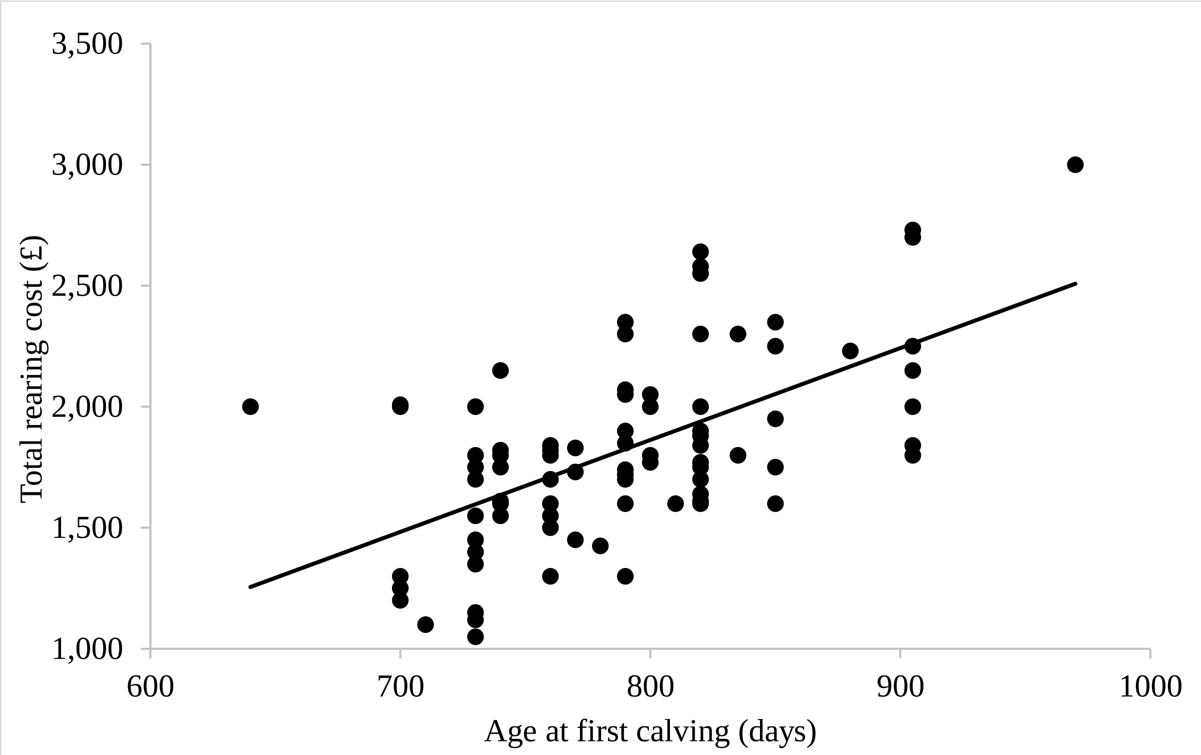


Figure 2.3: The relationship between the total cost of rearing and age at first calving. Adapted from Boulton et al. (2017); each symbol represents the data from one farm.

2.8.1 Factors Affecting Age at First Calving

Age at first calving is a product of management throughout the rearing period, and, as such, there are many aspects of the heifer rearing process that may influence AFC. Management in the pre (Shamay et al., 2005; Davis Rincker et al., 2011) and post-weaning period (Wathes et al., 2014) have the potential to reduce the pubertal age of the heifer. A younger pubertal age is beneficial because fertility improves with the number of estrus cycles experienced by a heifer (Byerley et al., 1987; Wathes et al., 2014). Therefore, heifers will be more likely to conceive, and as such, AFC will be reduced. Nevertheless, AFC is a function of the success of a breeding season; therefore, breeding management of heifers is important (Wathes et al., 2014). Estrus must be detected promptly. When using AI, those responsible for heat detection are competent (Diskin and Sreenan, 2000), particularly for heifers, as the duration of standing estrus varies from 12 to 14 hours (Diskin, 2008). During the breeding season, Heifer management will ensure that the pubertal heifer is inseminated early in the breeding season.

2.8.2 The Effect of Age at First Calving on Future Production

Age at first calving directly affects heifer rearing costs (Boulton et al., 2017); therefore, breeding heifers earlier to reduce AFC is often considered the best approach to shorten the non-productive period (Abeni et al., 2018). However, a younger AFC may have a negative effect on subsequent milk production (Berry and Cromie, 2009), reproduction (Wathes et al., 2008), calving performance (Mee et al., 2008b), and longevity (Eastham et al., 2018). This will be discussed in more detail in the following sections.

2.8.3 Milk Production

A reduction in AFC from 24 months of age to 23 months of age has been associated with suboptimal milk yield and MS production (Berry and Cromie 2009; Heinrichs and Heinrichs, 2011; Mohd Nor et al., 2013); however, this reduction appears to be confined to the first lactation (Wathes et al., 2014; Eastham et al., 2018). Increasing AFC may therefore be used to improve milk yield and MS production (Ettema and Santos, 2004; Berry and Cromie, 2009; Eastham et al., 2018).

2.8.4 Fertility

As previously mentioned, the relative importance of fertility in a seasonal calving system is more critical due to seasonal breeding constraints (Berry et al., 2013). If a heifer does not become pregnant early in the breeding season, she will not have the opportunity to be inseminated for a further 12 months (Moran and Chamberlain, 2017). There are added benefits associated with a younger AFC in a seasonal calving system such that the animal has adequate time to continue growing in the interval between first calving and the subsequent breeding season (Wathes et al., 2014), which begins each year on a predetermined date in April or May (Dillon et al., 1995). However, a very young AFC (<700 days of age) may be associated with impaired reproductive performance (Ettema and Santos, 2004; Berry and Cromie, 2009). Fertility performance was optimized in animal's calving for the first time, aged between 23 and 25 months (Cooke et al., 2013).

2.8.5 Survivability

Survivability, or stayability and longevity as it is often termed, is defined as the probability of an animal surviving to a specific age (Hudson and Van Vleck, 1981). Survivability is an essential aspect of heifer rearing; if a heifer does not remain in the herd long enough to repay the cost of rearing (Shalloo et al., 2014; Boulton et al., 2017). In a study by Brickell and Wathes (2011), 11% of heifers recruited were culled before first calving, therefore, affecting farm profitability. Age at first calving has also been associated with survivability; heifers that calved for the first time between 22 and 26 months of age were more likely to survive to subsequent lactations than their herd mates that were older than 26 months at first calving (Evans et al., 2006; Sherwin et al., 2016).

A study of UK dairy heifers reported that the AFC was 29.6 months, which had a negative association with survivability within the herd (Sherwin et al., 2016). Berry and Cromie (2009) delineated that heifers calving at 24 months had the greatest odds of survival compared to older parities.

2.8.6 Calving Performance

Dystocia is defined as calving difficulty resulting from prolonged spontaneous calving or prolonged severe assisted extraction (Mee, 2008b). Age at first calving may influence the incidence of dystocia, as calving difficulty is influenced by the age of the dam (Mee et al., 2008b). Thompson et al. (1983) found that a heifer calving as early as 22 months was not detrimental to calving performance. This is consistent with Berry and Cromie (2009), who found no effect of AFC on the likelihood of a difficult calving. Nevertheless, Mee et al. (2008b) delineated that the associations between AFC and calving difficulty may be due to immaturity. As such, achieving weight-for-age targets at calving is recommended to minimize the risk of calving difficulty.

In conclusion, ensuring that AFC is optimized will ensure that good milk production is achieved and that calving and fertility performance is favourable thereafter.

2.9 The Effect of Body Weight at First Calving on Future Production

It is widely accepted that BW at calving has a greater effect on production potential thereafter than that of age (Dobos et al., 2001; Archbold et al., 2012). Increasing the BW at first calving may effectively offset the adverse effects on production that accompany a decrease in AFC (Dobos et al., 2001). If heifers are too heavy at calving, it may be detrimental to production potential (Archbold et al., 2012). Similarly, milk production will be implicated if heifers are too light at calving (Handcock et al., 2018). The following section will review the associations between BW and dairy heifer production, reproduction, and health.

2.9.1 Milk Production

Body weight at first calving is fundamental to performance in the milking herd (Dobos et al., 2001; MacDonald et al., 2005). Although a linear relationship between BW at first calving and milk production (Dobos et al., 2001; McNaughton and Lopadell, 2013) has been reported, Handcock et al. (2019c) observed this relationship to be curvilinear, such that the milk yield response to increasing BW is greater in lighter heifers compared to that in heavier heifers. Heavier heifers at first calving also had higher peak milk yields, which is beneficial because peak milk yield is often correlated with total milk yield (Buckley et al., 2003; MacDonald et al., 2005). Nevertheless, the price a farmer is paid for their milk is dictated by MS production (Shalloo et al., 2007); therefore, the relationship between BW at first calving and MS production thereafter is more important. Although Berry et al. (2007b) observed an increase in milk protein concentration as calving BW increased; a study by Macdonald et al. (2005) reported these benefits to be exclusively in the first lactation. A 0.1% increase in milk protein and fat concentration equates to 0.9 and 0.4 €/kg MS (Shalloo and French, 2019), respectively increase in farm profit and ensure the prompt repayment of heifer rearing costs. Heavier heifers at calving have improved milk production during the first lactation (Macdonald et al., 2005; Martín et al., 2020). Heavier heifers at breeding often have improved milk production performance in the first lactation (Macdonald et al., 2005; Handcock et al., 2019c).

2.9.2 Udder Health

Somatic cells are essential indicators of mastitis in the herd (Hamann and Krömker, 1997). Mastitis has been identified as one of the most costly diseases on Irish dairy farms (Geary et al., 2012) such that a SCC of greater than 400 (‘000 cells/ml of milk) is consistent with a 2% reduction in farm profit (Dillon et al., 2015). Though heifers have not been milked previously, mastitis is still a significant source of concern for many dairy farmers. In a review of previous research, De Vliegher et al. (2012) reported a range of between 12 and 57% of quarters infected in heifers postpartum. An increase in SCC may be detrimental to milk yield (Kull et al., 2019) and longevity within the herd (Waage et al., 2000). Although a study by Berry et al. (2007a) found the likelihood of mastitis to increase with BW at calving, the association has not been widely discussed elsewhere.

2.10 Fertility

Heavier animals at first calving have higher nadir BW (Berry et al., 2006). This indicates the excessive mobilization of body reserves, and as such, these animals may have poor reproductive performance (Buckley et al., 2003; Poncheki et al., 2015). Infertility is a substantial cost on a dairy farm (Shalloo et al., 2014), particularly on seasonal calving dairy farms that depend on compact calving to ensure grass growth matches herd feed demand (Veerkamp et al., 2002). Although Crosse and Gleeson (1986) found no association between pre-calving BW and the number of services required for conception, Chebel et al. (2007) found that a 20 kg in BW increased the odds of conception by 0.5%. Heifers above target BW may be detrimental to subsequent calving intervals (Carson et al., 2002). Optimum BCS and BW are essential so that heifers can utilize body stores of nutrients to support milk production (Heinrichs et al., 1997). Associations between BW at calving and subsequent reproductive performance have also been reported in dairy cows (Roche et al., 2007c) with compromised reproduction in very heavy heifers (Dobos et al., 2001; Carson et al., 2002; Mc Naughton and Lopadell, 2013). Greater mobilization of body reserves in early lactation may delay the resumption of ovarian function (Butler and Smith, 1989; Roche et al., 2007), and as a result, the calving to conception interval is increased (Shrestha et al., 2004).

2.10.1 Calving Performance

It has been reported that having over-conditioned heifers prior to calving can result in fat deposits in the pelvic canal and consequently, calving problems can ensue (Hoffman and Funk, 1992; Hoffman, 1997; Bailey and Murphy, 2009). Mee et al. (2008b) reported that 5-10% of the variance in dystocia was attributed to maternal pelvic size. Dystocia and BW at first calving are often interlinked (Hoffman and Funk, 1992; Berry et al., 2007c; Gaafar et al., 2011). Dystocia costs up to €500 per case, therefore, may have economic implications for the Irish dairy farmer (McGuirk et al., 2007). Nevertheless, attaining the target BW of 85-90% at first calving may mitigate the associations between a younger AFC and dystocia (Mee et al., 2011).

2.10.2 Survivability

Heavier heifers generally have improved performance and, as such, survive longer in the herd (McNaughton and Lopdell, 2013). Survivability is a good measure of lifetime performance (Brickell and Wathes, 2011). Studies of UK dairy herds reported that only between 85.5 and 89% of HF heifers survived from birth to first calving (Brickell et al. 2009b; Cooke et al. 2013; Pritchard et al. 2013). Similar statistics are reported in New

Zealand dairy heifers (Compton, 2018), with heavier heifers more likely to remain in the herd until third calving than lighter ones (Handcock et al. 2019b). Nevertheless, there was a slight decline in survivability for the heaviest heifers (Handcock et al., 2019b); therefore, it was recommended that HF heifers weigh between 314 and 390 kg (i.e., between 45 and 65% of mature BW) at breeding to ensure longevity in the herd. Involuntary culling arising from reproductive inefficiency, mastitis, and lameness accounted for the largest proportion (33.4%) of culling on Canadian dairy farms between 2015 and 2020 (Roche et al., 2020). Nevertheless, there are positive associations between milk yield and longevity within the herd (Dallago et al., 2021). Larger, well-grown heifers are more productive (Archbold et al., 2012) and may not be as vulnerable to culling.

It is evident that BW at calving is important for production thereafter, the optimization of which will ensure that the heifer survives within the herd for a lengthy period. Achieving weight-for-age targets throughout the rearing period will optimize BW at first calving.

2.11 Milk Production

The main objective of rearing replacement heifers is to generate healthy cows that are able to fulfil their potential for milk production (Sejrsen, 2005). Milk production is one of the most important aspects of a dairy farm enterprise; this may be because farmers are paid for their milk on a monthly basis. There are many factors that affect milk production and will be reviewed in the following section.

2.11.1 Factors Affecting Milk Production

Many aspects of management throughout the rearing period (Terré et al., 2009; Archbold et al., 2012; Soberon et al., 2012a) can influence subsequent milk production of dairy heifers. The achievement of weight-for-age targets (Troccon, 1993) is widely recommended to optimize production potential in the lactating herd. However, milk production depends on management of the lactating herd (Kennedy et al., 2008) and is susceptible to other factors, such as genetics (Buckley et al., 2000), which are beyond the bounds of daily management decisions.

2.11.1.1 Body Weight and Body Condition Score

Body weight and BW gain throughout the rearing period determine the shape of the lactation curve. Soberon et al. (2012b) reported a linear relationship between BW gain in early life and milk production thereafter; for each additional kg of BW gain during the pre-weaning period, first lactation milk yield increased by on average 982 kg. Furthermore, heavier heifers at breeding (Macdonald et al., 2005; Archbold et al., 2012; Handcock et al., 2019c) have improved milk production performance. In a meta-analysis of eight studies, Heinrichs (2005) concluded that heifer BW gain of up to 0.8 kg/day before puberty would optimize first lactation milk production. The achievement of weight-for-age targets (Troccon, 1993), particularly in pasture-based systems where heifer growth may be variable (Handcock et al., 2021), is essential to optimize milk production. Although there is a positive relationship between BW (Carson et al., 2002) and BCS (Berry et al., 2003) at calving and milk yield thereafter, BW and BCS of the cow throughout the lactation are also important in terms of milk production (Berry et al., 2007b). This relationship was unsurprising because body tissue may be used in part to fuel milk production (Berry et al., 2003). Nevertheless, Berry et al. (2007b) reported that although the total milk yield was greatest for cows calving at a BCS of 4.25, cows calving at a BCS of 3.50 and 3.25 produced only 68 kg and 50 kg of milk less than those with a higher BCS at calving did.

2.11.1.2 Dry Matter Intake

Dry matter intake fuels milk production by supplying the animal with the necessary nutrients (Kennedy et al., 2008). Nevertheless, the feed requirements of a dairy cow change throughout lactation; a cow will reach peak milk production approximately 6-8 weeks after calving but will not reach peak DMI until 10-12 weeks after calving (Kavanagh, 2016). As such, early lactation feed management must be optimized to ensure that DMI is sufficient to support milk production. This is corroborated by Roche (2007a), who reported that a low DMI (8.6 kg/day) in early lactation would reduce milk fat and protein yield by 21 and 28%, respectively. Increasing concentrate supplementation in early lactation will benefit milk production; for each additional kg of concentrate consumed, there will be a 1.10 kg, 0.038 kg, and 0.032 kg increase in milk, protein, and fat, respectively (Kennedy et al., 2003; Kennedy et al., 2008). Kennedy et al. (2003) reported the association between concentrate supplementation and milk yield to be linear, the addition of which, therefore, may be used to avoid a negative energy balance in early lactation.

2.11.1.3 Transition Management

The transition period refers to the six-week period surrounding calving (Roche, 2007b) when cows are generally dried off to facilitate optimum milk production in the subsequent lactation (Pezeshki et al., 2010). The energy requirements of the cow during the dry period are to maintain BW and support BW gain of the calf in utero, as such; they are less than that during lactation (Grummer et al., 2004). Approximately three weeks before parturition DMI begins to decline and reduces dramatically in the week prior to parturition (Grummer, 1995; Murphy, 1999). Murphy (1999) reported that silage DMI declined from 10.4 kg/cow/day four weeks prior to calving to 6.4 kg/cow the week before calving; this may be due to the rapid growth of the foetus, which takes up space in the abdominal cavity and displaces rumen volume (Bertics et al., 1992). Therefore, cows are in a negative energy balance in the week prior to calving.

Nevertheless, feed management in the dry period may help to maintain energy intake, despite the inevitable decline in DMI. Although grass silage, which may be characterized by a low DMI, is the predominant feedstuff for pasture-based dairy cows during the transition period (McNamara et al., 2003), increasing the energy density of the diet pre-calving by supplementing with concentrate may benefit milk production. Pre-calving concentrate supplementation has the potential to increase both milk yield (Keady et al., 2005) and MS yield (McNamara et al., 2003). The length of the dry period may also influence milk production thereafter; although some studies have advised that the length of the dry period may be reduced slightly (Rastani et al., 2005), a 60-day (eight weeks) dry period is considered the optimum for milk production thereafter (Pezeshki et al., 2010). The transition from non-lactating, and thus relatively low nutrient requirements, to the extensive nutrient demands as milk production rapidly increases after parturition involves significant metabolic changes for the dairy cow (Reddy et al., 2016), as such metabolic diseases are common. Therefore, optimizing transition feed-management is important to ensure that negative energy balance, and thus metabolic disorders, are avoided.

2.11.1.4 Calving Performance

A difficult calving event, termed dystocia (Mee et al., 2008b), can have significant repercussions on the production potential of the heifer in early lactation; heifers produced significantly less milk following difficult calving (Berry et al., 2007c; Barrier and Haskell, 2011; McHugh et al., 2011). Dystocia costs €500 per case, including losses in milk yield and MS production (McGuirk et al., 2007), thus corroborating the associations between calving performance and production thereafter. A higher proportion of animals with severe difficulty during calving were culled from the herd (Dematawena and Berger, 1997; Tenhagen et al., 2007). The probability of calving difficulty increases linearly in heifers younger at first calving (Mee et al., 2011); therefore, an AFC of 25 months will ensure that calving difficulty is minimized.

2.11.1.5 Parity

Parity has a significant effect on milk production thereafter (Horan et al., 2005). First parity animals often have lower milk production and peak milk production; nevertheless, they have a higher lactation persistency (Tekerli et al., 2000; Horan et al., 2005) which means that the rate of decline in production after peak milk yield has been reached will not be as severe (Cole and Null, 2009). There is a linear increase in milk production with increasing parity (Lee and Kim, 2006), with Evans et al. (2006) reporting that first lactation animals produced 1378 and 483 kg less than those in lactation ≥3 did.

2.11.1.6 Genetic Merit

There has been much interest in the genetic improvement of dairy cows of late (Buckley et al., 2000). In Ireland, the EBI is used to select genetically superior animals during breeding (Berry et al., 2005). The national breeding objective is to generate cows with lower milk volume and higher fat and protein content; this aim is in line with the milk payment system in Ireland, in which farmers are rewarded for MS production and penalized for volume (Dillon et al., 2008). High genetic merit cows are reported to have increased yields of milk, fat, protein, and lactose (Buckley et al., 2000; Kennedy et al., 2003). Nevertheless, O'Sullivan et al. (2019) illustrated that cows with high genetic merit maintained higher production but with lower persistency than cows with national average genetic merit. In conclusion, although treatment throughout the rearing period is vital for milk production, environmental factors (i.e., BW, BCS, and DMI) and genetic factors may also influence performance.

2.12 Conclusion

In conclusion, despite the evident abundance of research on the pre-weaning management of dairy calves, there is no unanimous feeding strategy in the pre-weaning period in terms of colostrum, milk concentrate and roughage feeding, nor is there a universal method for the weaning of calves off milk. Furthermore, it is evident from the present review of literature, that research on the management of heifers at pasture is limited. Even more so, is the research on pasture-based heifers housed and offered conserved forages during the overwinter period. Much of the existing research on heifers has been undertaken in confinement systems of heifer rearing (Zanton and Heinrichs, 2008b; Van Amburgh et al., 2014), and may differ from that in Ireland, which is heavily reliant on grazed grass as a high quality, low cost feed source (Finneran et al., 2010; Läpple et al., 2012). Despite the heavy reliance on grazed grass as a feed source, there is no grassland management strategy specific to young ruminants. Differences aspects of which, i.e., pre and post grazing sward height (Ganche et al., 2013), and pre-grazing herbage mass (Kennedy et al., 2008), may have a profound impact on the feeding value of grass. Similarly, aspects of over-winter management, and their potential impact on heifer productivity, have also not been extensively researched.

Heifer growth is the most important aspect of a rearing strategy. In confinement systems of heifer rearing, precision nutrition is implemented to ensure that heifers are supplied with the exact nutrients necessary for growth (NRC, 2001; Zanton and Heinrichs, 2008b). In contrast, in pasture-based rearing systems, growth is a product of DMI from grass, silage and concentrate, the quality of which are often unknown prior to feeding. The dearth of research on pasture-based heifer DMI may be because it is inherently difficult to measure (Seymour et al., 2019). It is important, however, that DMI be quantified, in order to truly understand the mechanisms of heifer growth. Body weight is the most common indicator of heifer growth (Lukuyu et al., 2016); this may be due to its cohesion with weight-for-age targets, which are traditionally used for monitoring heifer progress (Troccon, 1993). Nevertheless, these targets were devised initially in confinement systems of heifer rearing, and it has been suggested that they are unsuitable for pasture-based rearing systems (Handcock et al., 2019b). The growth of a heifer throughout the rearing period also influences her fertility performance (Macdonald et al., 2005; Brickell et al., 2009b; Archbold et al., 2012), the relative importance of which is even more important in systems, such as Ireland, that impose seasonal breeding. The success of the seasonal breeding season will in turn influence AFC, which is one of the biggest determinants of heifer rearing costs (Boulton et al., 2017). The heifer rearing strategy implemented may affect the performance of a heifer thereafter in the milking herd (Soberon et al., 2012a; Handcock et al., 2019c; Martín et al., 2020), it is therefore imperative that the long-term impact of different rearing strategies, on heifer growth, DMI and fertility performance, be investigated. This was, therefore, the aim of this thesis. It was hypothesized that delaying weaning, and feeding a heifer intensively thereafter, would result in well-grown heifers that had superior DMI and fertility performance.

Chapter 3: Using body weight to develop equations to predict the dry matter intake of pasture-based heifers reared using different strategies

Journal of Dairy Science (Submitted)

3.1 Abstract

Dry matter intake is one of the key components of a heifer rearing strategy; however, despite its importance in terms of achieving weight-for-age targets and maximizing pasture utilization, the DMI of pasture-based heifers has not been widely researched. In order to determine the effect of different rearing strategies on the DMI of pasture-based heifers, data were collected from HF (n=124), and JE (n=56) heifers weaned at either eight or 12 weeks and subsequently offered either a low or high post-weaning feeding regime. The *n*-alkane technique was used to establish the DMI of heifers on nine occasions throughout the rearing period. Environmental factors (i.e., nutrition and management) had a greater effect on DMI than that of weaning age. Although HF heifers had a higher total DMI than the JE, JE heifers had a higher DMI when expressed as a percentage of BW. The data in the present study were used to formulate an equation based on BW, to predict the DMI of pasture-based dairy heifers throughout the rearing period. Establishing the DMI of pasture-based dairy heifers throughout the rearing period will allow farmers to allocate pasture accurately and achieve the dual pasture management objectives of high animal performance while maximizing pasture utilization.

3.2 Introduction

Dry matter intake is intrinsic to BW gain and is, therefore, an important aspect of heifer rearing (Quigley et al., 1985). Much of the previous research on heifer DMI has been undertaken in confinement systems of heifer rearing, where DMI prediction equations are used to formulate TMR diets and ensure heifer ADG is constant (Quigley et al., 1986b; Zanton and Heinrichs, 2008b). However, the DMI of pasture-based dairy heifers, for whom BW gain is the predominant energy sink (NRC, 2001), has not been extensively researched. In pasture-based production systems, factors such as the variability of grass growth and quality (Hennessy et al., 2020) influence DMI (O' Donovan and Delaby, 2008), making it more difficult for replacement heifers to achieve target BW described by Troccon (1993) and in Chapter 4 of the present thesis.

Establishing DMI is vital in understanding the performance and efficiency of animals reared at pasture (McGovern et al., 2021). Commonly expressed as a percentage of BW, DMI ranges from 1.3 to 4.4% of heifer BW (NRC, 2001; Hoffman and Kester, 2013). Pasture allowance has a direct effect on both heifer DMI and BW gain (Patterson et al., 2018), the accurate allocation of which will ensure heifers achieve BW targets, outlined by Troccon (1993) and in further detail in Chapter 4 of the present thesis, and avoid grass wastage (Fulkerson et al., 2005). However, as there has been limited research on the DMI of heifers at pasture, creating an equation to predict DMI from heifer BW would equip farmers with the knowledge necessary to allocate sufficient pasture to support BW gain while also ensuring high pasture utilization in subsequent rotations.

While pasture management practices can influence DMI (e.g., pasture allowance, post-grazing height; Patterson et al., 2018), animal management may also have an effect. Weaning calves from milk and introducing pasture at an early age may increase grass DMI and reduce rearing costs (Boulton et al., 2017). However, variation in grass growth and quality (Hennessy et al., 2020), coupled with the limitations of a seasonal breeding period (e.g., 12-weeks; Berry et al., 2013), may result in heifers having insufficient DMI to attain target BW at key time points, e.g., breeding. As such, pasture management may need to be altered, or concentrate supplementation may be required to ensure that heifers have the DMI necessary to support BW gain prior to breeding (Roche et al., 2015). Grazing behaviour and DMI vary with breed (Prendiville et al., 2010), particularly HF and JE, as there is a considerable difference in BW (Prendiville et al., 2011a). Therefore, it is essential that, in predicting DMI, breed be accounted for.

To the best of the author's knowledge, the DMI of pasture-based dairy heifers has not previously been quantified; therefore, the objective of the present study was firstly to establish the DMI of pasture-based HF and JE heifers throughout the rearing period, when weaned at different ages and offered diverging feeding regimes post-weaning. Secondly, the study sought to devise a series of equations to predict DMI from BW of pasture-based HF and JE heifers; doing so would have practical significance for the attainment of heifer weight-for-age targets and pasture utilization. It was hypothesized that later weaned HF and JE heifers fed a high feeding regime in the post-weaning period would have a higher DMI, and that equations to predict the DMI of pasture-based heifers would have a high prediction accuracy.

3.3 Materials and Methods

This study was carried out on the Dairygold Research Farm at Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Kilworth, Co. Cork, Ireland (52°09′N 8°16′W) between February 2018 and November 2020. Ethical approval was granted by the Teagasc Animal Ethics Committee (TAEC) (TAEC129/2016), and procedure authorization was granted by the Irish Health Products Regulatory Authority (HPRA) (AE19132/P070). All experiments were conducted in accordance with the Cruelty to Animals Act (Ireland 1876, as amended by European Communities Regulations 2002 and 2005) and the European Community Directive 86/609/EC.

3.3.1 Experimental Treatments and Animals

This study contained a subset of heifers, which participated in a larger research project that evaluated the relationship between weaning age, post-weaning feeding regime, and growth during the rearing period, which is outlined in Chapter 4. The experimental treatment of the animals throughout the rearing period is described hereafter in brief. A 2 (two weaning ages; eight-week weaned [8w], and 12-week weaned [12w]) x 2 (two post-weaning planes of nutrition; high [H] and low [L]) factorial design was in place. A total of 254 heifers were enrolled in the full study; however, DMI was estimated using 180 of these heifers (60 per year for three years; numbers based on sample size calculations). At birth, the study investigators randomly assigned each heifer to a treatment group; however, care was taken to ensure treatment groups were balanced for mean bBW, breed, and date of birth. Dry matter intake was estimated on 15 heifers from each experimental treatment group i.e., 12wH (n=15), 12wL (n=15), 8wH (n=15) and 8wL (n=15). Only the purebred HF and JE heifers were assigned to the study. The experimental dataset for DMI estimation comprised of heifers born in 2018 (n=44 HF with a mean bBW of 34.9 ± 4.73 kg and n=16 JE with a mean bBW of 22.8 ± 2.21 kg), 2019 (n=40 HF with a mean bBW 35.1 ± 3.98 kg and n=20 JE with a mean bBW 24.4 ± 2.85 kg) and in 2020 (n=40 HF with a mean bBW 34.3 ± 3.94 kg and n=20 JE with a mean bBW 21.9 ± 1.89 kg). The bBW of HF and JE heifers in the DMI estimation dataset were representative of those enrolled in the full study. The heifers born in 2018, 2019, and 2020 will be referred to as Y1, Y2, and Y3, respectively, from here on. Dry matter intake was estimated nine times in total (between two and four times per group of heifers) throughout the rearing period.

Treatments were not blinded, as different feed allocations had to be offered. The timeline of DMI estimation periods is outlined in Figure 3.1.

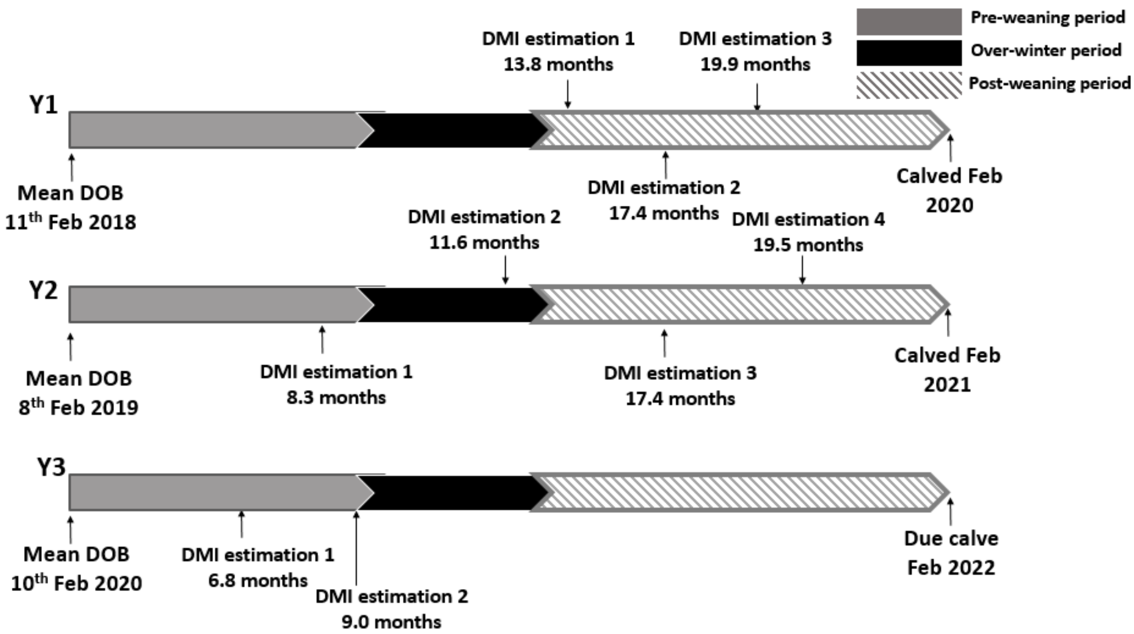


Figure 3.1: Timeline of dry matter intake (DMI) estimation periods across year one (Y1), year two (Y2) and year three (Y3) born pasture-based dairy heifers.

3.3.2 Pre-weaning Heifer Management

3.3.2.1 Colostrum and Transition Milk Feeding

At birth, calves were removed from their dam as a biosecurity measure (McGuirk and Collins, 2004). Calves were subsequently tagged, weighed (TruTest XR3000, Tru-test Limited, Auckland, New Zealand), and their navel was sprayed with 10% iodine to prevent infection (Mee, 2008a). Calves received good quality colostrum (≥22% Brix value; 3 litres within two hours of birth) and five feeds of transition milk (2 L/feed) over a three-day period in straw-bedded individual pens (1.3m x 0.8m). Colostrum and transition milk were refrigerated (Cummins et al. 2017) and warmed in a tepid water bath prior to feeding.

3.3.2.2 Milk Replacer Feeding

Calves were grouped by age, irrespective of treatment, in an effort to avoid confounding factors.

Once they had received all of their colostrum and transition milk feeds, they remained in these group pens (9.5 x 4.8m) containing approximately 20 calves until weaning. The group pens consisted of a concrete feed space with a straw-bedded lie back area. Calves had access to an automatic milk feeder (Vario Smart Powder, Förster–Technik) and were fed 26% CP MR (Volac Heiferlac) reconstituted at 15%. Over the first seven days, MR allowance was gradually increased from 4 L/MR/day to 6 L/MR/day; this volume remained constant until seven days prior to weaning (8w or 12w). Milk replacer allowance was then gradually reduced over seven days. Calves had access to a continuous supply of fresh, clean drinking water, straw, and concentrates (Sweet Start Calf Starter Pencils, Southern Milling, Cork, Ireland; 20% CP, 7.2% crude fibre, and 9.2% ash;) throughout the housing period. Calves were checked twice daily, and if they were found to be ill, they received the appropriate care and veterinary treatment. All treatments given to calves were recorded.

3.3.3 Heifer Management Post-Weaning

3.3.3.1 First Grazing Season

As described Chapters 4, 5, and 6, following weaning, heifers were grouped by their post-weaning feeding regime (H or L) and grazed perennial ryegrass swards (>80%) in rotation until winter housing. The H and L groups were grazed adjacent to one another separated by a temporary electric fence to ensure that they had access to pasture of similar quality. Both the H and L groups received a fresh grass allocation every 2-3 days. The H and L heifers were offered 1.5-2.5 and 0.5-1.5 kg concentrate/heifer/day ([Dairygold Prime Elite Kaf Gro, Dairygold Co-Operative Society Ltd, Lombardstown Mill, Mallow, Co. Cork, Ireland; 16% CP, 10% crude fibre and 5.9% ash] and [Dairygold Beeflav, Dairygold Co-Operative Society Ltd, Lombardstown Mill, Mallow, Co. Cork; 16% CP, 10% crude fiber and 5.9% ash]), respectively, depending on grass quality and availability.

3.3.3.2 *Over-Winter*

Over-winter management was similar for H and L heifers within year of birth, as is described in Chapter 4. For the first three weeks of winter, Y1 and Y2 heifers were offered *in-situ* Red Start (a kale and rape hybrid forage crop), ad-libitum hay, and 1 kg concentrates/heifer/day (Dairygold Beeflav, Dairygold Co-Operative Society Ltd, Lombardstown Mill, Mallow, Co. Cork; 16% CP, 10% crude fibre and 5.9% ash). Heifers were then group-housed in a slatted shed with a concrete lie-back, where grass silage (64-67% DMD) and 1.5-2 kg concentrate/heifer/day were offered (Roche's Feeds Heifer Rearer 20% CP) along the feed barrier each morning at approximately 10:00 am. Uneaten silage was 'pushed in' to the feed barrier each evening at approximately 16:00 pm. For the final six weeks of the over-winter period during Y1 and Y2, heifers were turned out and offered a forage crop (Red Start, as described above), ad-libitum hay, and 1 kg concentrate/heifer/day.

3.3.3.3 Second Grazing Season

Similar to as is described in Chapter 4, in their second grazing season, heifers were re-grouped by treatment (H or L) and offered an all-grass diet. In the second grazing season post-weaning, the H and L heifers were instead allocated different DHA, which was adjusted daily, to achieve target post-grazing sward heights of 4.5 and 3.5 cm, respectively. In order to ensure grass of similar quality was offered to each treatment group, they were grazed adjacent to one another and separated by an electric fence. Fresh grass was allocated every 2-3 days once the target post-grazing heights of 4.5 and 3.5 cm (Jenquip, Feilding, New Zealand) for the H and L heifers, respectively, had been achieved. Fresh, clean drinking water was continuously available.

3.3.4 Grassland Management

Weekly farm walks were undertaken to estimate the quantity of grass available in each paddock (kg DM/ha), and data were subsequently recorded in PastureBase Ireland (Hanrahan et al., 2017) to aid the selection of the most suitable paddocks for grazing. Pre-grazing yields of 1,400-1,600 kg DM/ha (> 4 cm) were targeted. Pasture allocations (m^2) were measured using a trundle wheel (DW-PRO; Caulfield Industrial Ltd., Oranmore Business Park, Oranmore, Co. Galway, Ireland).

Pre-grazing herbage mass was determined weekly by cutting a 0.25 m^2 quadrant to 4 cm using a Gardena hand-held electric shears (Accu 60; Gardena International GmbH, Ulm, Germany). The herbage from each cut was placed in a plastic bag and weighed using a hanging scale (Super Samson; Salter, Smethwick, West Midlands, UK). To determine

DM percentage, a subsample (~100 g) of each cut was dried overnight at 90°C. The DM yield per hectare was calculated using the formula below (O' Donovan and Dillon, 1999):

$$\text{Yield (kg DM/ha)} = \text{Fresh weight (g) x DM \% x 0.4}$$

Weekly samples (~100 g) were also taken to targeted post-grazing height and dried for approximately 16 hours at 60°C to determine grass quality. Pre and post-grazing sward heights (cm) were determined for each area allocated before and after grazing, respectively, by taking approximately 50 sward height measurements across the diagonal of the paddock using a rising plate meter (Jenquip, Feilding, New Zealand).

During the DMI measurement periods, H and L heifers were allocated fresh grass each day. Daily herbage allowance for each group of heifers was calculated using the following equation (O' Donovan and Dillon, 1999):

$$\text{Area } (\text{m}^2/\text{day}) = \frac{\text{Number of animals x DHA (kg) x } 10{,}000(\text{m}^2)}{\text{DM yield (kg DM per ha)}}$$

3.3.5 The *n*-alkane Technique

The DMI of the heifers was estimated using the *n*-alkane technique outlined by Mayes et al. (1986) and modified by Dillon and Stakelum (1989). Heifers were dosed once per day with paper pellets (Carl Roth, GmbH, Karlsruhe, Germany) containing C32-alkane (n-dotriacontane). Dosing took place at the same time each day (approximately 9:00 am) for 11 consecutive days. The concentration of C32-alkane in the paper pellet was proportionate to the weight of the heifers; in the first year post-weaning, heifers (approximately 241 ± 30.5 days of age and 184 ± 35.7 kg) were dosed with a 200 mg of C32-alkane (*n*-dotriacontane). In the second year post-weaning, heifers (approximately

488 ± 84.6 days of age and 378 ± 83.8 kg) were dosed with 400 mg of C32-alkane (*n*-dotriacontane). Dotriacontane was dissolved using a heptane solvent and pipetted onto the boluses; the boluses were then left aside so that the solvent would evaporate before oven drying.

Herbage offered to heifers from days 6 to 11 of the DMI estimation period was sampled (Accu 60; Gardena International GmbH, Ulm, Germany) to the height they were defoliating pastures. The grass was sampled to 4 cm for both L and H heifers in the first grazing season post-weaning and 3.5 and 4.5 cm for the L and H heifers, respectively, in the second grazing season post-weaning. Fifty grass samples were taken per allocation per day, prior to grazing, in a 'W' pattern to get a representative sample of the herbage offered. The grass samples were frozen at -20°C after collection. During the over-winter DMI estimation period, two representative silage samples were taken immediately after feeding daily at different intervals along the feed barrier. The silage samples were frozen at -20°C after collection. A representative concentrate sample was taken each day when the heifers were supplemented with concentrates during DMI estimation periods (i.e., in the first grazing season and overwinter).

Similarly, faeces were sampled from day six to 11, inclusive, from approximately 7:30 am until 9:00 am and again from 3:00 pm until 4:30 pm. Naturally-voided faeces samples were largely obtained during periods of field observation. In the holding yard, rectal grab samples were taken from the heifers from whom no fecal sample had been collected during the period of field observation (approx. 9.3% of heifers had to be rectally grab-sampled). No more than three attempts were made to take a grab sample from a heifer. Following collection, the faeces samples were frozen at -20°C.

3.3.5.1 Intake Sample Analysis

Fecal samples collected during DMI estimation periods were gently thawed, bulked (14.4 g /sample), placed in a 40°C oven for 48 hours before being milled using a 1-mm sieve, and analysed for C32. Frozen grass and silage samples were bowl-chopped, freeze-dried, dried in a 40°C oven for 48 hours, and milled through a 1-mm screen prior to chemical analysis for C33 (tritriacontane). Concentrate samples collected during DMI estimation periods were dried in a 60°C oven for 24 hours before being milled through a 1-mm screen prior to chemical analysis for C33.

The ratio of naturally occurring C33-alkane in the herbage to dosed C32-alkane in the faeces samples was used to calculate DMI.

3.3.5.2 Grass, Concentrate and Silage Sample Analysis

Composite samples of herbage taken in 2019 and 2020 were dried for approximately 16 hours at 90°C to determine DM percentage. Composite samples of herbage taken in 2019 were dried for approximately 16 hours at 60°C to determine quality. Composite silage samples were also dried for approximately 16 hours at 40°C to determine quality. The aforementioned herbage and silage samples were subsequently milled. In 2020, restrictions due to the global SARS-CoV-2 pandemic meant that herbage samples were instead stored at -20°C before being freeze-dried and milled. Composite samples of concentrates were dried for approximately 16 hours at 60°C to determine quality. Grass and concentrate samples were analysed using near-infrared spectroscopy (Foss-NIR System DK, Hillerød, Denmark) for ash, CP, OM Digestibility, NDF, and ADF using a NIR equation derived from Burns et al. (2012). The OM digestibility and CP of silage samples were analysed using wet chemistry similar to Claffey et al. (2019). The remaining quality parameters of the silage samples were determined using near-infrared spectroscopy (Foss-NIR System DK, Hillerød, Denmark).

3.3.6 Body Weight Measurement

Body weight was measured using an electronic weighing scale (TruTest XR 3000, Tru-test Limited, Auckland, New Zealand) during each DMI estimation period to determine the DMI of each heifer as a percentage of BW. Average daily gain from birth to each DMI estimation period and between DMI estimation periods, respectively, was calculated by regressing BW measurements on time.

3.3.7 Statistical Analysis

3.3.7.1 Grass Measurements

Statistical analyses were conducted using SAS (version 9.4; SAS Institute Inc., Cary, NC). The effects of post-weaning feeding regime in each grazing season on pre-grazing herbage mass, pre-gazing sward height, post-grazing sward height, DHA, concentrate allowance, total daily feed allowance, and chemical composition of the herbage offered were analysed using linear mixed models (PROC MIXED).

3.3.7.2 Effect of Weaning Age and Post-Weaning Feeding Regime on Dry Matter Intake

Dry matter intake was assessed using linear mixed models in PROC MIXED. Dry matter intake estimation periods with similar average ages were grouped for analysis. Fixed effects included in the models investigating DMI and DMI as a percentage of BW were pre and post-weaning treatment, the interaction between pre and post-weaning treatment, and breed. Birth BW was centred within a breed and included in the models as a covariate. Significant associations were confirmed when $P < 0.05$ and least-square means were assessed.

3.3.7.3 Creating Equations to Predict Dry Matter Intake

Non-linear regressions of BW on DMI were tested (PROC REG) across the entire dataset and then for HF and JE separately. Stratifying the dataset by breed group was found to increase the accuracy of prediction, therefore verifying that separate comprehensive equations were required to predict the DMI of pasture-based JE and HF heifers. Within-herd validation involved stratifying the HF and JE datasets by birth year, pre and post-weaning treatment.

Approximately 33% of records from each stratum in both the HF and JE datasets were removed for validation. The remaining records from each stratum were used to create the equations, such that heifers were not present in the calibration and validation data sets simultaneously. This process was repeated three times for each HF and JE dataset, respectively until all records had been tested using within-herd validation once. Non-linear regressions of BW on total DMI were then performed for both HF and JE datasets. The association between predicted and actual DMI was assessed using regression analysis. The statistical methodology used to evaluate the accuracy of DMI predicted by the model compared with actual DMI on 33% of the data was similar to that of Ruelle et al. (2019) and Costigan et al. (2021).

In brief, the R^2, RMSE, the slope of the line, MSPE, RPE, and CCC were used to determine if the model accurately predicted DMI. The MSPE is the sum of three components: mean bias $(M_m – P_m)^2$, line variation $S^2_p (1 – b)^2$ and random variation about the line, $S^2_m (1 - R^2)$, whereby each is expressed as a proportion of the total MSPE:

$$MSPE = \frac{\sum(M-P)^2}{n}$$

$$= (M_m - P_m)^2 + S^2_p(1-b)^2 + S^2_m(1-R^2)$$

where n is number of records, M and P are measured and predicted DMI, respectively, Mm and Pm are mean values of M and P, respectively, S_m^2 and S_P^2 are variances of M and P, respectively, b is the slope of the line of P regressed on M; and R^2 is the coefficient of determination of the line. The RMSPE is the root of the MSPE. The RPE is calculated as:

$$\text{RPE} = \left(\frac{RMSPE}{M_m}\right) \times 100$$

The CCC is comprised of two components:

$$\text{CCC} = p \times Cb$$

where p is the Pearson correlation coefficient and Cb is the bias correction factor:

$$Cb = \frac{2 \times \sigma_m \times \sigma_p}{\sigma_m^2 + \sigma^2{}_p + \left(\mu_m - \mu_p\right)^2}$$

and σ_m, σ_p, μ_m, and μ_P are the standard deviation and average of the measured and predicted data, respectively. The CCC evaluates the correlation between the actual and predicted DMI and the deviation from the 45° line.

3.4 Results

The effect of post-weaning feeding regime on pre-grazing herbage mass, pre and post-grazing sward heights, and herbage and concentrate allowances is reported in Table 3.1.

Pre-grazing sward heights and pre-grazing herbage mass were similar for H and L heifers, while differences in concentrate allowances and post-grazing sward heights for H and L heifers during DMI estimation periods in the first and second grazing seasons were in line with defined targets. The effect of the post-weaning feeding regime on the chemical analysis of the herbage offered during periods of DMI estimation is outlined in Table 3.2. The herbage offered to H and L heifers during DMI estimation periods was of similar quality within a grazing season.

3.4.1 Effect of Treatment and Breed on Body Weight and Dry Matter Intake as a Percentage of Body Weight

There was no effect of weaning age, nor was there an interaction between weaning age and post-weaning feeding regime for DMI was expressed as a percentage of BW. With the exception of at 12.7 months of age, post-weaning feeding regime was associated ($P<0.001$) with heifer DMI as a percentage of BW; the DMI as a percentage of BW of H and L heifers ranged from 2.2 to 2.9%, and from 2.1 to 2.5%, respectively. The H heifers were significantly ($P<0.05$) heavier than the L heifers from 8.7 months of age (Table 3.3).

Holstein-Friesians were significantly heavier than JE ($P<0.001$) during each DMI estimation period (Table 3.4), however, JE had a significantly higher DMI as a percentage of BW compared to HF (Figure 3.2).

Table 3.1: The effect of post-weaning feeding regime (high or low) on pre-grazing herbage mass, pre and post-grazing sward height, herbage, concentrate and total daily feed allowance during dry intake matter estimation periods in the first and second grazing season.

	Grazing season 1				Grazing season 2			
	High	Low	S.E.	Pr > F	High	Low	S.E.	Pr > F
Pre-grazing herbage mass (kg of DM/ha)	1486	1453	34.2	0.504	1679	1705	39.0	0.640
Pre-grazing sward height (cm)	10.7	10.1	0.26	0.101	10.7	10.3	0.23	0.284
Post-grazing sward height (cm)	4.4	4.5	0.09	0.422	5.2	3.7	0.08	<0.001
Herbage allowance (kg of DM/heifer per day)	5.3	5.1	0.70	0.918	9.3	6.1	0.30	<0.001
Concentrate allowance (kg/heifer per day)[1]	1.5	0.5	0.05	<0.001	-	-	-	-
Total daily feed allowance (kg of DM/heifer per day)	6.7	5.6	0.29	0.015	9.3	6.1	0.28	0.006

[1] There was no concentrate offered in the second grazing season

Table 3.2: The effect of post-weaning feeding regime (high or low) on the chemical composition of grass offered to heifers during dry matter estimation periods in the first and second grazing season, and over-winter period.

	Grazing season 1				Grazing season 2				Silage	
	High	Low	S.E.	Pr > F	High	Low	S.E.	Pr > F	All treatments	S.E.
Dry matter%	14.0	13.7	0.31	0.589	16.5	16.3	0.30	0.298	32.0	14.84
OM digestibility	848.8	836.2	5.70	0.125	847.2	841.1	6.65	0.519	ND	ND
CP	225.2	219.8	8.09	0.639	187.4	191.8	4.23	0.471	12.5	3.79
ADF	237.2	242.6	5.20	0.467	220.3	217.5	6.05	0.747	99.4	6.43
NDF	366.3	383.8	6.97	0.082	361.8	363.5	7.28	0.865	153.4	10.03
Ash	87.6	92.4	3.53	0.345	75.6	79.1	2.78	0.365	28.9	0.86

ND = not determined.

Table 3.3: Effect of weaning age (Pre), post-weaning feeding regime (Post), the interaction between weaning age and post-weaning feeding regime (Pre*Post), and breed on the body weight (kg) of Holstein-Friesian (HF) and Jersey (JE) heifers.

	Pre*Post					Breed			Pr > F			
	8		12		S.E.	HF	JE	S.E.	Pre	Post	Pre*Post	Breed
Age (months)	high	low	high	low								
6.7	151	148	156	152	4.5	174	129	3.3	0.279	0.406	0.845	<0.001
8.7	191	180	201	177	3.8	212	162	2.8	0.344	<0.001	0.095	<0.001
12.7	255	244	260	240	5.2	281	219	3.8	0.970	0.004	0.389	<0.001
17.4	366	350	375	345	5.9	402	316	4.4	0.733	0.001	0.220	<0.001
19.7	417	402	424	400	6.3	457	366	4.7	0.695	0.002	0.401	<0.001

Table 3.4: Effect of weaning age (Pre), post-weaning feeding regime (Post), the interaction between weaning age and post-weaning feeding regime (Pre*Post), and breed on the dry matter intake (kg) of Holstein-Friesian (HF) and Jersey (JE).

	Pre*Post					Breed			Pr > F			
	8		12		S.E.	HF	JE	S.E.	Pre	Post	Pre*Post	Breed
Age (months)	high	low	high	low								
6.7	4.3	3.5	4.2	3.6	0.10	4.2	3.6	0.08	0.770	<.0001	0.600	<.0001
8.7	4.7	3.8	4.9	4.0	0.11	4.5	4.1	0.08	0.158	<.0001	0.774	0.001
12.7	5.2[a]	5.4[ab]	5.5[b]	5.3[ab]	0.09	5.7	5.1	0.06	0.417	0.966	0.013	<.0001
17.4	7.9	7.5	8.0	7.3	0.13	7.8	7.5	0.09	0.862	<.0001	0.222	0.020
19.7	9.5[a]	8.9[b]	10.1[c]	8.8[b]	0.19	9.7	8.9	0.14	0.163	<.0001	0.057	0.006

[a-c] Means within a row without a common superscript differ

3.4.2 Effect of Treatment and Breed on Dry Matter Intake

The interaction between weaning age and post-weaning feeding regime for DMI was significant at 12.7 months of age (P=0.013; Table 3.4) and tended to be significant at 19.7 months of age (P=0.057). At 12.7 months of age, the 12wH heifers had a DMI of 0.3 kg/heifer/day more than the 8wH heifers, while all other treatments were similar. At 19.7 months of age, the 8wL and 12wL had similar DMI, while the 8wH and 12wH were significantly different from each other and all other treatments.

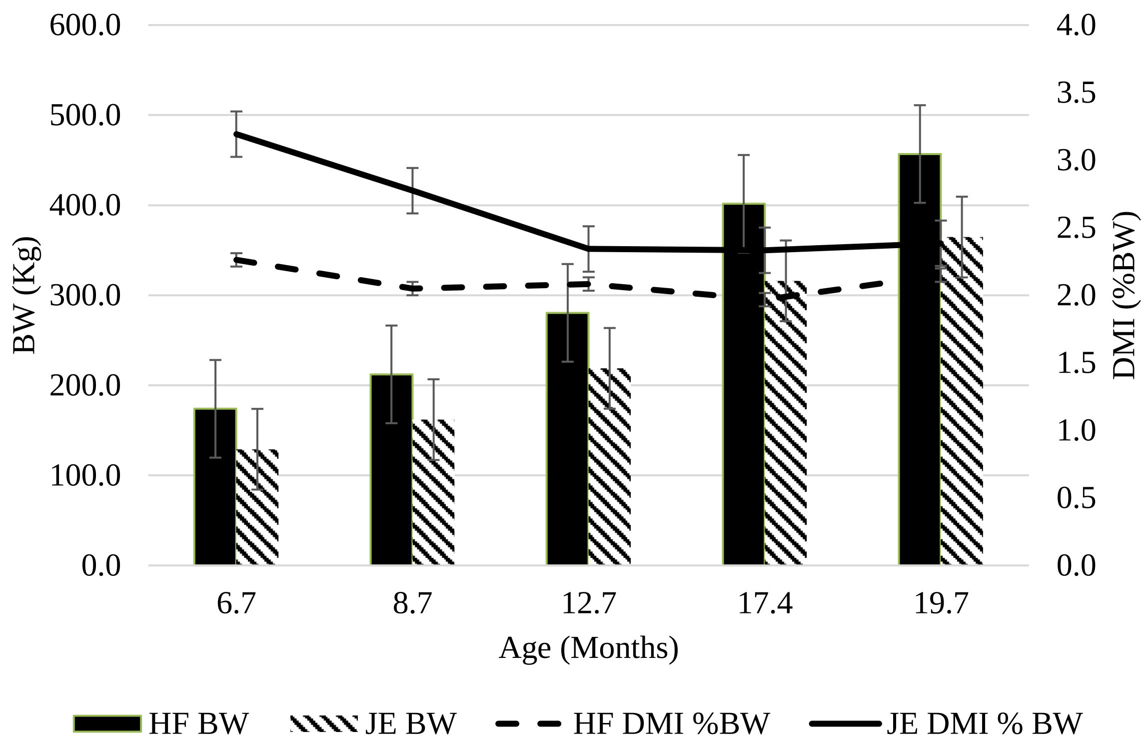


Figure 3.2: The effect of breed on body weight (BW) and dry matter intake (DMI) as a percentage of BW (DMI % BW) of Holstein-Friesian (HF) and Jersey (JE) heifers during periods of dry matter intake estimation.

There was no significant effect of weaning age on DMI. With the exception of at 12.7 months of age, the DMI of the H heifers was significantly (P<0.001) higher (≥0.6 kg/heifer/day) than that of the L heifers. Holstein-Friesian heifers had significantly higher intakes than JE (P<0.05) during every intake estimation period; HF consumed between 0.3 and 0.7 kg DM/heifer/day more than JE throughout the rearing period.

3.4.3 Dry Matter Intake Prediction Equations

The fitting statistics for the equations to predict the DMI of HF and JE heifers are outlined in Table 3.5; values reported are the average of the three iterations for the HF and JE within-herd validations, respectively.

Table 3.5: Comparison between the measured and predicted dry matter intake (kg) of pasture-based Holstein-Friesian (HF) and Jersey (JE) heifers using within herd validation.

	Validation									
					Proportion of MSPE					
	Measured	Predicted	Slope	RMSPE	Mean	Line	Random	RPE	CCC	Cbias
HF	6.69	6.67	0.99	0.92	1.1	6.2	92.7	13.8	0.92	0.99
JE	6.09	6.07	0.98	0.81	1.9	3.7	94.4	13.2	0.92	0.99

[1]RMSPE = root mean square prediction error; MSPE = mean square prediction error; RPE = relative predicted error; CCC = concordance correlation coefficient; Cbias = bias of the concordance correlation coefficient

Both equations were found to accurately predict DMI, with RPE values of 13.8% and 13.2% for HF and JE, respectively. A high proportion of MSPE (>92.7%) was attributable to random variation. The equations to predict DMI of HF and JE heifers had average R^2 and RMSE values of 0.84 and 0.89 kg, and 0.86 and 0.80 kg, respectively. The regression equations used to predict DMI for HF and JE heifers are presented in Table 3.6.

Table 3.6: Non-linear equations to predict dry matter intake using body weight (BW; kg) of pasture-based Holstein-Friesian (HF) and Jersey (JE) heifers.

	Equation	R^2	RMSE
HF	$0.038 \times BW^{0.9}$	0.843	0.89
JE	$0.043 \times BW^{0.9}$	0.858	0.80

[1]RMSE = root mean square error

3.5 Discussion

Dry matter intake provides the foundation for heifer ADG and, as such, the attainment of weight-for-age targets (Troccon, 1993). Although the DMI of heifers reared in confinement is well understood (NRC, 2001), the same is not valid for heifers reared at pasture.

3.5.1 Dry Matter Intake Prediction Equations

Dry matter intake prediction equations are widely utilized; however, it is generally under the guise of precision nutrition in countries where heifers are housed year-round and offered a feed of consistently good quality (Zanton and Heinrichs et al., 2008b). In precision nutrition regimes, diets are designed to supply specific nutrient densities to optimize heifer growth (NRC, 2001). In pasture-based heifer rearing systems, grass is the predominant feed of the heifer, the quality of which can vary significantly due to grazing management decisions (Kennedy et al., 2006; Ganche et al., 2013) and changeable weather conditions (Dillon et al., 2006; Ruelle et al., 2018). The financial success of a grazing system is underpinned by pasture utilization (Ramsbottom et al., 2015). As such, good animal performance is achieved while simultaneously maximizing pasture utilization (Ganche et al., 2013). Maximizing pasture utilization and as such ensuring the availability of high-quality pasture in subsequent rotations (O'Donovan and Delaby, 2008) is a challenge faced by pasture-based dairy farmers. If the DMI of the heifer throughout the rearing period is established, pasture can be allocated proportionately, thus increasing pasture utilization and reducing pasture wastage (Fulkerson et al., 2005).

Similar to that reported by Prendiville et al. (2010), whereby the DMI of the JE cows was 87.4% of the HF, there were significant differences in the DMI of HF and JE heifers in the present study; the DMI of the JE ranged from 85.7 to 96.2% of that of the HF throughout the rearing period. Therefore, it was hypothesized that different DMI prediction equations would be required for the HF and JE heifers; the creation of separate equations decreased the RMSE by 0.06 and 0.12 kg for the HF and JE, respectively. Although the DMI prediction equations formulated for HF and JE heifers in the present study were based solely on heifer BW, with R^2 of 0.84 and 0.86, respectively, and MSPE values of 1.1 and 1.9%, respectively, the equations were highly accurate. This was similar to the NRC (2001; $R^2 = 0.84$), Quigley et al. (1986b; MSPE of 1.47%), and NRC (2001; MSPE of 1.48%) equations which were created to predict the DMI of Holstein heifers, and are widely used in diet formulation. Furthermore, the coefficients of equations in the present study were very similar to that reported by INRA (2010); the coefficients for HF and JE in the present study were 0.038 and 0.043, respectively, while the coefficient reported by INRA was 0.039. Although the prediction accuracy of the aforementioned equations (NRC, 2001; Quigley et al., 1986b; INRA, 2010) may be due to the inclusion of digestible nutrients, the success of the present equation is a product of the data with which it was created (i.e., data obtained using the *n*-alkane technique (Savian et al., 2018; Seymour et al., 2019).

In comparison to previously published equations, the equation proposed in the present study is simple yet accurate, and it is suitable for predicting the DMI of pasture-based dairy heifers. It is practical for use on a pasture-based dairy farm because it is based on a trait (i.e., BW) that may be readily measured by a farmer using electronic scales. In establishing the DMI of their heifers as they grow, farmers may tailor their grassland management decisions to avoid pasture wastage, which will, in turn, increase profitability (Ramsbottom et al., 2015). Exclusively pasture-based diets can supply the BW gain required by heifers (Patterson et al., 2018) to ensure that weight-for-age targets, set out by Troccon (1993) and outlined in Chapter 4 in this thesis, are achieved. However, an imbalance between pasture allowance and DMI of the heifer will result in pasture wastage, which will affect the farm system's economic resilience (Macdonald et al., 2018). Regular use of the proposed equation, in conjunction with the observation of post-grazing heights, will ensure that heifer DMI and thus weight-for-age targets of 30, 60, and 90% of mature BW at six, 15, and 24 months (Troccon, 1993) are optimized in a cost-effective manner.

3.5.2 Effect of Treatment on Dry Matter Intake

There has been renewed interest in pre-weaning nutrition of late, both because it may influence future performance (Khan et al., 2011; Soberon and Van Amburgh, 2013) and because it accounts for the most significant proportion of heifer rearing costs (Boulton et al., 2017). In accordance with the present study's findings, there was no carryover effect of pre-weaning treatment on DMI or BW in the post-weaning period in studies by Haisan et al. (2018) and Bruinjé et al. (2019). Differences in the DMI of 8w and 12w heifers throughout the rearing period were ≤ 0.3 kg; as such, different weaning ages may be implemented without detriment to the DMI profile thereafter. In the present study, there was, however, an interaction between weaning age and post-weaning feeding regime for DMI at 12.7 and 19.7 months, which, although was statistically significant, may not be biologically significant (i.e., the difference in DMI between treatment groups was $\leq$ 6%). Although generally accurate at predicting DMI, there may be individual variability of *n*-alkane recoveries, which may explain the discrepancies in DMI at 12.7 and 19.7 months of age.

Environmental factors (i.e., nutrition and management) in the present study had a greater influence on DMI than that of weaning age, as is evidenced by the significantly higher DMI of the H heifers for the most part of the rearing period, which was as a direct result of additional concentrates and pasture consumed in the first and second grazing seasons, respectively. This verifies that grassland management strategies, such as varying stocking rate and pasture allowance (Horan et al., 2004; Coffey et al., 2017), are effective in regulating heifer DMI. As a result of higher DMI achieved by the H heifers (between 0.6 and 1.0 kg higher than the L), they had a BW advantage of between 16 and 23 kg in the second grazing season, and as such, greater attainment of BW targets. Post-weaning feed management is therefore important in terms of optimizing both heifer DMI and consequently, weight-for-age targets (Troccon, 1993)

There is a linear relationship between DMI and BW (Quigley et al., 1986a); therefore, DMI as a percentage of BW, or intake capacity as it is often termed, is also regularly used to describe DMI. There was no difference in the DMI as a percentage of BW of H and L heifers at 12.7 months as this estimation period coincided with the over-winter feeding period. This indicates that when offered a common diet, DMI is the same for all heifers irrespective of treatment group; the L heifers did not compensate for a lower feed allowance in the previous grazing season. Therefore, heifers must be offered their required allowance throughout the first grazing season to ensure they have adequate DMI and, as such, achieve the weight-for-age target at breeding. In the first grazing season (i.e., when heifers were 6.7 and 8.7 months of age), the H heifers had a DMI of 0.4% of BW higher than that of the L. In the second grazing season (i.e., when the heifers were 17.4 and 19.7 months of age), the DMI as a percentage of BW advantage maintained by the H heifers had reduced to 0.2%. This is consistent with previous research, whereby DMI as a percentage of heifer BW decreased as BW increased (NRC, 2001; Hoffman and Kester, 2013). This may be due to high feed efficiency in early life (Lammers et al., 1999), but it may also be due to the concentrate, which is the feed of choice for dairy heifers (DeVries and von Keyserlingk, 2009), that was offered in the first grazing season. Although increasing concentrate supplementation may be concomitant with an increase in DMI, at a cost ratio of grazed grass to concentrates of 1:2.4 (Finneran et al., 2010), it is unfavourably associated with the cost of heifer rearing (Boulton et al., 2017).

3.5.3 Effect of Breed on Dry Matter Intake

There are inherent differences between HF and JE in terms of growth (Handcock et al., 2019a), DMI (Prendiville et al., 2010), and performance in the milking herd (Vance et al., 2013). It was therefore unsurprising that the HF heifers in the present study had significantly higher DMI than JE throughout the rearing period. Prendiville et al. (2010) observed a similar pattern in HF and JE dairy cows and attributed the differences in DMI between breed groups to grazing behaviour. Similar to that reported by Coffey et al. (2017) and Prendiville et al. (2009), where crossbred and JE cows, respectively, had a higher DMI as a proportion of BW, the JE heifers in the present study had higher intakes when expressed as a percentage of BW. This indicates that JE heifers have a higher intake capacity than HF and may be facilitated by a larger digestive tract (Goddard and Grainger, 2004; Beecher et al., 2014). It is also reported that animals with high intake capacities may be more efficient in the lactating herd (Prendiville et al., 2010); however, validating this theory on the present heifers was outside the objectives of the study.

3.6 Conclusion

Heifer DMI was more responsive to post-weaning feed management than it was to weaning age. Therefore, different rearing strategies may be used to manipulate DMI and consequently, optimize BW gain. Although HF had a higher total daily DMI, JE heifers had a higher intake capacity. The proposed equation to predict the DMI of pasture-based dairy heifers will facilitate a better understanding of the associations between DMI and BW of pasture-based HF and JE heifers. Establishing the DMI of pasture-based heifers will help farmers to make more educated grassland management decisions, and as such, the achievement of weight-for-age targets will be more cost-effective.

Chapter 4: The Development of Standard Body Weight Curves to Reflect the Growth Pattern of Pasture-Based Holstein-Friesian and Jersey Heifers

Journal of Dairy Science (Submitted)

4.1 Abstract

The attainment of weight-for-age targets is one of the most important key performance indicators in a heifer rearing system. However, current targets assume a linear trajectory of growth, which is almost impossible in pasture-based heifer rearing systems due to seasonal variation in grass growth and quality. This problem may be further exacerbated in systems that house animals during the winter, causing stagnation of growth. In order to establish the pattern of growth of heifers reared under different management strategies and to validate if current weight-for-age targets were suitable, data were collected from HF (n=177) and JE (n=77) heifers that were weaned at either eight or 12 weeks and subsequently offered either a high or low feeding regime in the post-weaning period. An equation was created that calculated the growth trajectory of heifers, based on their bBW and age at turnout to the second grazing season. The growth pattern of heifers from the equation developed in the present study is best described as sigmoidal in shape. Although the heifers weaned at 12 weeks and subsequently offered a high post-weaning feeding regime had the greatest attainment of target weight, existing weight-for-age targets were achievable for heifers reared under different management strategies. Additional weight-for-age targets created using the proposed equation will complement the current targets and ensure pasture-based heifer growth is optimized prior to breeding.

4.2 Introduction

Growth is one of the most important aspects of a heifer rearing program, the optimization of which will ensure that the heifer has achieved puberty prior to the breeding season and will subsequently calve at <26 months of age (Froidmont et al., 2013; ICBF, 2019). This is particularly significant in pasture-based seasonal calving systems, where the objective is for the calving season to coincide with the grass-growing season to ensure that the feed demand of the herd matches grass supply (Dillon et al., 1995). Although age also plays an integral part in puberty, the effect of age, compared to that of BW, on production potential thereafter is less pronounced (Archbold et al., 2012). If a heifer has not achieved the BW necessary to attain puberty, become pregnant early in the breeding season and subsequently calve between 22 and 26 months, she will not have the opportunity to calve again for a further 12 months, and her non-productive lifespan will be extended (ICBF, 2019).

Weight-for-age targets of 30%, 60%, and 90% of mature BW at six, 15, and 24 months (Troccon, 1993), respectively, are traditionally used to ensure that heifers are well grown throughout the rearing period, and thus have attained puberty before the breeding season begins (Wathes et al., 2014). Furthermore, heifers that achieve the aforementioned targets will have improved performance thereafter (Ettema and Santos, 2004; Wathes et al., 2008; Archbold et al., 2012). Nevertheless, these targets (Troccon, 1993) were devised in confinement systems of heifer rearing, where feed of consistently good quality was offered throughout the rearing period (Washburn et al., 2002). The aforementioned targets also assume a linear growth trajectory; however, in pasture-based rearing systems, such as that in Ireland and New Zealand, the growth trajectory of the young heifer is not linear (Handcock et al., 2016) due to the management system imposed. The current weight-for-age targets have not been validated in a rearing system where heifer growth commonly stagnates over winter (McNaughton and Lopdell, 2012) when grass silage, which is commonly of substandard quality (Kavanagh et al., 2016), is the predominant feedstuff. Furthermore, weight-for-age targets are a function of mature BW, the miscalculation of which will result in heifers that are either under or overgrown relative to target weight

(Handcock et al., 2019a). Previous studies have found large variation in the mature BW of pasture-based dairy heifers is possible (DairyNZ, 2015).

Maximizing the length of the pre-weaning feeding period is commonly used to take advantage of high feed efficiency in early life (Hill et al., 2009; Eckert et al., 2015). Although early life nutrition may influence long-term performance (Soberon et al., 2012b), the daily costs incurred in the milk-feeding period are significantly higher than those incurred during the remainder of the heifer rearing period (Boulton et al., 2017). Therefore, increasing the length of the milk-feeding period may not be economically viable. Alternatively, intensified feeding in the post-weaning period by, for example, increasing concentrate supplementation or altering grassland management strategies, may ensure weight-for-age targets at breeding and consequently, first calving are achieved (Gardner et al., 1977; Hoffman et al., 1997; Lammers et al., 1999). Furthermore, BW differs with breed group (Prendiville et al., 2009; Handcock et al., 2019b); therefore, separate weight-for-age targets may be required for pasture-based heifers of different breeds, for example, HF and JE.

The objective of the present study was to establish the growth trajectory of pasture-based winter-housed HF and JE heifers and devise an equation to predict individual growth, from birth until calving, using bBW and age at turnout to the second grazing period. The study also sought to evaluate if existing weight-for-age targets were suitable for pasture-based winter-housed heifers reared using different management strategies and, if necessary, create additional targets at, for example, housing and turnout, which would complement the management of pasture-based dairy heifers. Finally, it aimed to determine the effect of different rearing strategies on the BW, and attainment of target BW, of pasture-based HF and JE heifers from birth to 24 months. It was hypothesized that equations would accurately predict individual HF and JE heifer growth throughout the rearing period, and that new weight-for-age targets would be required for pasture-based HF and JE heifers, and finally, that later weaned heifers, offered a high feeding regime in the post-weaning period would be heavier throughout the rearing period.

4.3 Materials and Methods

The study was undertaken on the Dairygold Research Farm at Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Kilworth, Co. Cork, Ireland (52°09′N 8°16′W) between February 2018 and February 2021. The Teagasc Animal Ethics Committee (TAEC) (TAEC129/2016) granted ethical approval, and the Irish Health Products Regulatory Authority (HPRA) (AE19132/P070) granted procedure authorization. All experiments were conducted in accordance with the Cruelty to Animals Act (Ireland 1876, as amended by European Communities Regulations 2002 and 2005) and the European Community Directive 86/609/EC.

4.3.1 Experimental Design

The heifers in the present study were also part of other studies in Chapters 3, 5 and 6. The study was a 2 (weaning ages; 8w or 12w) x 2 (post-weaning planes of nutrition; H or L) factorial design. Only purebred HF and JE heifers were assigned to the study. The study population consisted of heifers born in 2018 (n=62 HF mean bBW 34.4 ± 4.67 kg and n=26 JE mean bBW of 23.0 ± 2.38 kg), 2019 (n=68 HF mean bBW 35.2 ± 4.23 kg and n=31 JE mean bBW 24.5 ± 2.88 kg) and 2020 (n=47 HF mean bBW 34.2 ± 4.18 kg and n=20 JE mean bBW of 21.9 ± 1.94 kg). A spring calving system was in place such that the mean birth dates of 2018, 2019, and 2020 born heifers were February 10 ± 12.8 days, February 9 ± 12.7 days, and February 10 ± 9.9 days, respectively. The heifers born in

2018, 2019, and 2020 will henceforth be referred to as Y1, Y2, and Y3, respectively. At birth, calves were balanced for bBW, breed, and date of birth before being randomly assigned to one of four experimental treatment groups by study investigators. The four groups were as follows; 12wH (n=66), 12wL (n=65), 8wH (n=61) and 8wL (n=62). Treatments were not blinded, as different feed allocations had to be offered.

4.3.2 Pre-Weaning Heifer Management

4.3.2.1 Colostrum and Transition Milk Feeding

Management was in line with best practice newborn calf care (Barry et al., 2020) and was described in more detail in Chapters 3 and 5. In brief, calves received three litres of good quality colostrum (Bielmann et al., 2010) from a single dam within two hours of birth, collected from freshly calved cows at the nearest scheduled milking time (07:30h or 15:00h). After colostrum feeding, calves received five feeds of transition milk (Blum and Hammon, 2000) in their individual pens at a rate of 4 L/day.

4.3.2.2 Milk Replacer Feeding

When calves had received all of their feeds of colostrum and transition milk (three days of age), they were moved to a large pen containing approximately 20 calves where they were grouped by age and not treatment; this was an effort to avoid confounding factors. The indoor group pens (9.5 x 4.8m) consisted of a concrete feeding area with a straw-bedded lie back, and calves remained in the same pen until weaning. Calves were fed 26% CP MR (Volac Heiferlac; Volac, Church St, Portaliff Glebe, Killashandra, Co. Cavan; 26% CP, 16% crude oils and fats, 7% crude ash) at a rate of 150g MR/L water using an automatic feeder (Vario Smart Powder, TAP5–VS1–50: Förster–Technik GmbH, Gerwigstrasse 25, D – 78234 Engen, Germany). Over their first seven days on the feeder, the volume of MR offered to the calves was gradually increased from four to six L MR/day. The daily MR allowance was offered in three equal feeds freshly prepared in one-litre portions at 37 ºC. The volume of MR remained constant at 6 L MR/day until eight days before each calf reached their respective weaning age (eight or 12 weeks), at which point the volume of MR offered was gradually reduced over seven days. Overall, the 8w and 12w weaned calves were offered on average 49.4 and 74.6 kg of MR, respectively, during the pre-weaning period.

4.3.3 Post-Weaning Heifer Management

4.3.3.1 First Grazing Season

After weaning, calves were regrouped according to their post-weaning treatment group (H or L) and rotationally-grazed predominantly perennial ryegrass swards until they were removed from pasture and assigned to their winter diets the following winter. The H and L heifers grazed next to one another, separated by a temporary electric fence, to ensure both groups had access to grass of similar quality. Differences in post-weaning feeding regimes were created by feeding contrasting levels of concentrates (Dairygold Beeflav, Dairygold Co-Operative Society Ltd, Lombardstown Mill, Mallow, Co. Cork; 16% CP, 10% crude fibre, and 5.9% ash). Calves assigned to H and L post-weaning treatments were offered 1.5-2.5 kg and 0.5-1.5 kg concentrate/heifer/day, respectively, depending on grass quality and availability.

4.3.3.2 First Over-Winter Period

Over-winter management was similar for treatments within year of birth, as is outlined in Chapters 3, 5 and 6. For the first three weeks of winter, Y1 (November 30 - December 17) and Y2 heifers (November 25 – December 18) grazed *in-situ* forage brassica

(Redstart), in addition to *ad-libitum* hay and 1 kg concentrates/heifer/day (Dairygold Beeflav, Dairygold Co-Operative Society Ltd, Lombardstown Mill, Mallow, Co. Cork; 16% CP, 10% crude fibre and 5.9% ash). Heifers were then housed for approximately seven weeks, during which time grass silage (64-67% DMD) and 1.5-2 kg concentrate/heifer/day were offered (Roche's Feeds Heifer Rearer 20%; Roches feeds, Dock Road, Co. Limerick; 20% CP). Total over-winter concentrate supplementation was the same for all heifers. For the final six weeks of the over-winter period Y1 (February 7 – March 19) and Y2 (February 4 – March 18), heifers were turned out and once again offered *in-situ* forage brassica (Redstart), *ad-libitum* hay, and 1 kg concentrate/heifer/day (Roche's Feeds Heifer Rearer 20%; Roches feeds, Dock Road, Co. Limerick; 20% CP). Heifers were re-grouped by post-weaning treatment (H or L) before being turned out to grass for their second grazing season.

Y3 heifers were housed for the entire duration of the over-winter period (November 9 - March 17) and fed grass silage (64-67% DMD) and 0.5-1.0 kg concentrate/heifer/day (Dairygold Beeflav, Dairygold Co-Operative Society Ltd, Lombardstown Mill, Mallow, Co. Cork; 16% CP, 10% crude fibre and 5.9% ash).

4.3.3.3 Second Grazing Season

The second grazing season for the Y1 and Y2 heifers was from March 19 – November 25 and March 18 – October 22, respectively. As the experiment finished in February 2021, data were not collected for the second grazing season of the Y3 heifers. Heifers (Y1 and Y2) were re-grouped by post-weaning treatment (H or L) and offered an exclusively pasture-based diet. Contrasting pasture allowances were offered to create differences between treatment groups such that post-grazing sward heights (rising plate meter; Jenquip, Feilding, New Zealand) of 4.5 and 3.5 cm were targeted for the H and L treatment groups, respectively.

4.3.3.4 Second Over-Winter Period

Over-winter management was similar for treatments within year of birth. The Y1 and Y2 heifers were housed for their second winter on October 16 and 22, respectively, when they were approximately 20.6 months of age. As is standard practice for animals during the transition period (Kavanagh, 2016), the heifers were offered a diet of *ad-libitum* silage (64-67% DMD) for the remainder of the experimental period until they were approximately 24 months of age.

4.3.4 Grassland Management

Grassland management was similar to that of O' Donovan and Dillon (1999) and Claffey et al. (2019). Weekly grass walks were undertaken to estimate pasture availability in each paddock and fresh grass (>4 cm) was allocated to both grazing groups (H and L) every two to three days. Pre and post-grazing sward height and the area (m^2) of each allocation was determined before and after grazing. Composite samples of herbage were dried for approximately 16 hours at 90°C, and 16 hours at 60°C to determine DM percentage and grass quality, respectively. Grass quality samples were analysed using near infrared reflectance spectroscopy (Foss-NIR System DK, Hillerød, Denmark) for ash, CP, OM digestibility, NDF, and ADF using a NIR equation derived from Burns et al. (2012).

4.3.5 Body Weight Measurement

Body weight was measured at birth and every two weeks thereafter until housing at 10 months of age, after which it was measured monthly until calving at 24 months using electronic weighing scales (TruTest XR 3000, Tru-test Limited, Auckland, New Zealand). The weighing scales were calibrated prior to use using known weights. Average daily gain was calculated by regressing BW measurements over the trial period.

4.3.6 Analysis

Statistical analyses were conducted using SAS (version 9.4; SAS Institute Inc., Cary, NC).

4.3.6.1 Grass Measurements

The effects of post-weaning feeding regime in each grazing season on pre-grazing herbage mass, pre-grazing sward height, post-grazing sward height, DHA, concentrate allowance, total daily feed allowance, and chemical composition of the herbage offered were analysed using linear mixed models (PROC MIXED).

4.3.6.2 Effect of Weaning Age and Post-Weaning Feeding Regime on Body Weight

Outliers were eliminated within breed and treatment groups. Data were declared outliers if the difference between the observed and predicted BW was greater than or equal to three times the RMSE. Approximately 1.15% of the data were outliers and were therefore excluded from further analysis. Data were only collected for the Y3 heifers until they were 12 months of age; therefore, BW was analysed separately from one to 11 months and 12 until 24 months. The associations between weaning age, post-weaning feeding regime, and BW at standard ages were assessed using linear mixed models in PROC MIXED. In all models, the heifer was included as a random effect, and standard age was included as repeated effects, with an autoregressive covariance structure used to model the association among the repeated measurements. Factors considered in the model investigating BW were weaning age, post-weaning treatment, the interaction between weaning age and post-weaning treatment, breed, and standard age. Birth BW was centred within a breed and subsequently included in the models as a covariate. Significant associations were confirmed when $P < 0.05$ and least-square means were subsequently assessed.

4.3.6.3 Creating Equations to Predict Heifer Body Weight

The data were graphed by treatment and breed group; the resulting growth curves had an obvious point of inflection that coincided with the turnout to the second grazing season. Therefore, the subsequent analysis involved creating two combined sigmoidal models to account for both the first and second grazing seasons. A point of intersection, which corresponded with the turnout to the second grazing season, joined the aforementioned sigmoidal models. The sigmoidal model to describe heifer BW was as follows;

$$BW = \frac{A_i}{(1+\exp^{(B_i \times (C_i - age))})}$$

where Ai corresponded to the BW asymptote at the end of each respective period, Bi was the constant to determine the curvature of the growth pattern, and Ci corresponded to the age at the point of inflection. The Solver tool (Microsoft Excel Solver; Microsoft Corp., Redmond, WA), which applies a generalized reduced gradient non-linear optimization technique, was used to minimize the sum of squares of the difference between the measured BW and predicted BW calculated from the regression analysis (Lasdon et al., 1973). The aforementioned sigmoidal model was used to predict the BW coefficients of each treatment and breed group separately. There was a high degree of similarity between coefficients for treatment within breed group; therefore, the coefficients were averaged for treatment within breed group. According to these combined sigmoidal curves, separate models, using bBW and age at the second grazing turnout as input variables, were created for both HF and JE and subsequently used to calculate standard BW from birth in seven-day increments.

4.4 Results

The effect of post-weaning feeding regime on pre-grazing herbage mass, pre and post-grazing sward heights, herbage and concentrate allowances in each grazing season is reported in Table 4.1.

Pre-grazing sward heights and pre-grazing mass were similar for H and L heifers, while differences in concentrate allowances in the first grazing season and post-grazing sward heights in the second grazing season were significantly different (P<0.001) for H and L heifers in line with targets. The effect of the post-weaning feeding regime on the quality of herbage offered during each grazing season is reported in Table 4.2. The herbage offered to H and L heifers in the first and second grazing seasons was of similar quality. Herbage quality was also similar between years.

There was no residual effect of weaning age on BW from 12 to 24 months (Table 4.4). The H heifers were significantly heavier than the L heifers at 12 (P=0.002) and 15 months (P=0.031). The interaction between weaning age and post-weaning feeding regime for BW at 12 months tended towards significance (P=0.091). At 12 months, the 12wL heifers were significantly lighter (22.8 kg) than the 12wH heifers. The interaction between weaning age and post-weaning feeding regime tended to be significant at 24 months (P=0.088); the 12wH heifers had BW similar to that of the 8wH (11.8 kg difference), but 12.9 and 16.9 kg higher than 8wL and 12wL, respectively. The 8wH had BW similar to that of the 8wL and 12wL (a difference of 1.1 and 5.1 kg, respectively) at 24 months.

At all time-points throughout the experiment, the HF heifers were significantly heavier than JE (P<0.001).

Table 4.1: The effect of post-weaning feeding regime (high or low) on pre-grazing herbage mass, pre and post-grazing sward height, herbage, concentrate and total daily feed allowance during the first and second grazing season.

	Grazing season 1				Grazing season 2			
	High	Low	S.E.	Pr > F	High	Low	S.E.	Pr > F
Pre-grazing herbage mass (kg of DM/ha)	1584	1523	28.9	0.139	1806	1743	28.1	0.112
Pre-grazing sward height (cm)	10.2	10.2	0.15	0.933	11.2	11.2	0.18	0.856
Post-grazing sward height (cm)	4.7	4.5	0.07	0.092	5.0	3.8	0.05	<0.001
Herbage allowance (kg of DM/heifer per day)	4.5	4.5	0.23	0.898	10.0	7.0	0.18	<0.001
Concentrate allowance (kg/heifer per day)[1]	1.7	0.8	0.04	<0.001	-	-	-	-
Total daily feed allowance (kg of DM/heifer per day)	6.1	5.3	0.24	0.015	10.0	7.0	0.18	<0.001

[1] There was no concentrate offered in the second grazing season

Table 4.2: The effect of post-weaning feeding regime (high or low) on the chemical composition of grass offered to heifers in the first and second grazing season.

	Grazing season 1				Grazing season 2			
	High	Low	S.E.	Pr > F	High	Low	S.E.	Pr > F
DM (%)	16.4	17.0	0.53	0.498	17.3	17.2	0.49	0.858
OM Digestibility	816.9	817.0	6.44	0.992	835.8	832.5	7.57	0.759
CP	204.5	194.3	6.19	0.247	193.9	196.2	6.76	0.809
ADF	224.3	225.4	4.85	0.868	227.9	230.8	5.89	0.722
NDF	379.9	383.5	5.92	0.666	364.3	367.1	5.92	0.811
Ash	79.9	78.6	2.66	0.724	80.0	81.2	3.83	0.828

Table 4.3: Effect of weaning age (Pre), post-weaning feeding regime (Post), the interaction between weaning age and post-weaning feeding regime (Pre*Post), and breed on body weight (kg) of Holstein-Friesian (HF) and Jersey (JE) heifers at standardized ages from one to 11 months of age.

	Treatment								Breed			
	8 weeks		12 weeks			Pr>F						Pr >F
	High	Low	High	Low	SE	Pre	Post	Pre*Post	HF	JE	SE	
1 month	41.8	42.1	42.4	41.6	2.08	0.973	0.916	0.795	48.1	35.9	1.53	<0.001
3 month	77.0	79.4	86.5	84.6	2.08	0.004	0.891	0.282	93.0	70.8	1.53	<0.001
6 month	138.4	140.1	145.5	141.0	2.08	0.049	0.488	0.129	161.0	121.6	1.53	<0.001
11 month	237.2	226.7	244.7	226.3	2.08	0.085	<.001	0.052	262.9	204.5	1.53	<0.001

Table 4.4: Effect of weaning age (Pre), post-weaning feeding regime (Post), the interaction between weaning age and post-weaning feeding regime (Pre*Post), and breed on body weight (kg) of Holstein-Friesian (HF) and Jersey (JE) heifers at standardized ages from 12 to 24 months of age.

	Treatment								Breed			
	8 weeks		12 weeks			Pr>F						Pr >F
	High	Low	High	Low	SE	Pre	Post	Pre*Post	HF	JE	SE	
12 month	252.2	245.2	262.0	239.2	4.77	0.695	0.002	0.091	279.1	220.2	3.50	<0.001
15 month	292.9	284.4	295.2	283.5	4.77	0.888	0.031	0.727	323.9	254.0	3.50	<0.001
20 month	401.9	399.2	414.8	401.2	4.77	0.113	0.080	0.248	450.9	357.6	3.50	<0.001
24 month	478.8	477.7	490.6	473.7	4.77	0.418	0.051	0.088	534.9	425.4	3.50	<0.001

4.4.1 Equations to Predict Body Weight of Pasture-Based Heifers

Equations were initially created to predict the BW of each treatment and breed group; however, as coefficients were so similar for treatment within breed group, the coefficients of the equations were balanced for HF and JE within treatment groups to develop two comprehensive equations to predict the BW of pasture-based HF and JE heifers from birth until calving. The equation proposed to predict the BW of a pasture-based HF or JE heifer at a given age (days) in the first year of life, i.e., prior to turn out to the second grazing season, is as follows:

$$\frac{8.7(bBW)}{[1 + e^{(A\times(B-age))}]}$$

The equation proposed to predict the BW of a pasture-based HF or JE heifer at a given age (days) after turnout to the second grazing season is as follows:

$$\frac{(2 \times \left(8.7(bBW)\right) \times Z)}{[1 + e^{(C\times(AT2-age))}]}$$

with

$$Z = 1 + e^{(A\times(170-AT2)}$$

where AT2 is age at turnout to second season at grass.

The coefficients A, B and C are 0.012, 170 and 0.0079 for the HF. Similarly, the coefficients A, B and C are 0.0127, 170 and 0.0084 for the JE.

The standard growth curves created for pasture-based HF and JE heifers, weighing 35 and 25 kg, respectively, at birth and aged 415 days at turnout to grass for their second grazing season, are sigmoidal in shape (Figure 4.1). The age at turnout for their second grazing season, i.e., the intersection between the two sigmoidal curves, was defined as the difference (in days) between the date of the turnout for the second grazing season and the birth date of the heifer.

For the purpose of the present analysis, the birth date was defined as February 1, the age at turnout for their second grazing season was chosen as April 1 the following year, and the bBW of the HF and JE heifers was defined as 35 and 25 kg, respectively. Consequently, the age at turnout to the second grazing season was 415 days. The mature BW of HF and JE heifers in the present study was predicted to be 573 kg and 448 kg, respectively. A higher proportion of the 12wH heifers attained weight-for-age targets at six (42.6%), 15 (43.8%) and 24 (62.5%) months, compared to the 8wH (28.3, 28.3 and 34.8% at six, 15 and 24 months, respectively), 12wL (21.7, 28.3 and 52.3% at six, 15, and 24 months, respectively) and 8wL (36.2, 31.9 and 48.9% at six, 15 and 24 months, respectively) heifers.

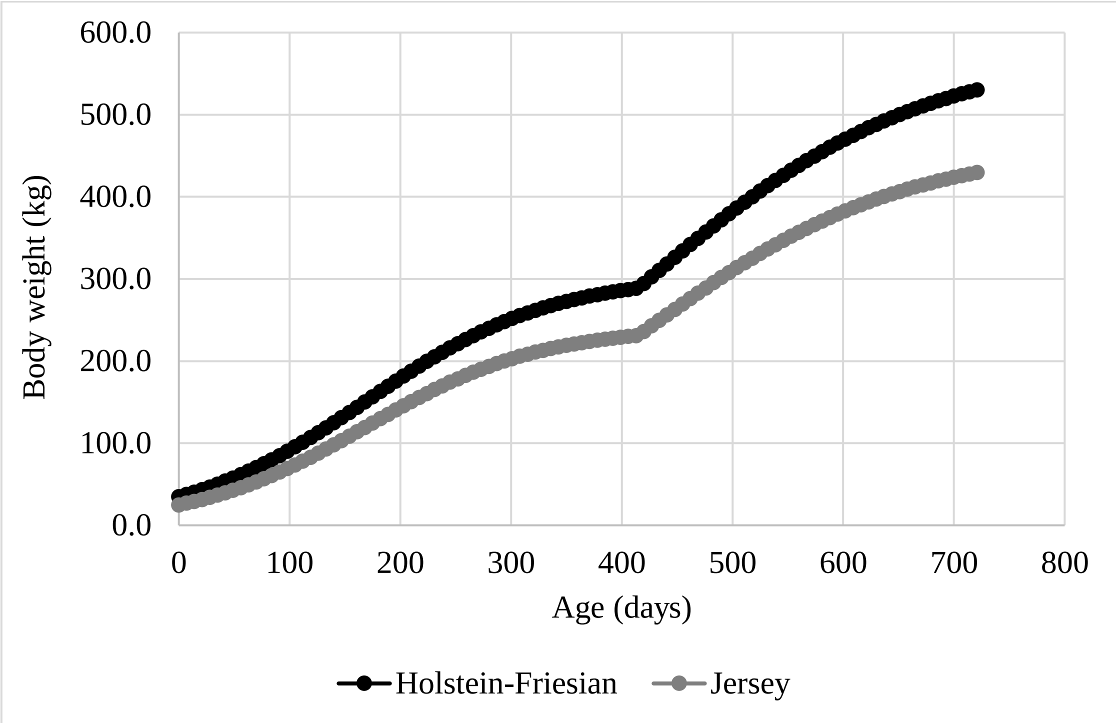


Figure 4.1: Growth curves, from birth until calving, of Holstein-Friesian (black) and Jersey (grey) heifers, weighing approximately 35 and 25 kg, respectively, at birth and aged 415 days at turnout to the second grazing season.

4.5 Discussion

Heifer BW varies with rearing system; heifers reared in confinement may be heavier than those reared at pasture due to precision nutrition feeding regimes (Roche et al., 2015). However, heifer BW also varies within a system, as is evident from the diversity in heifer BW reported in a study of commercial pasture-based farms by Archbold et al. (2012). Despite the reported variation in heifer BW within different heifer rearing systems, the objective is to rear heifers in line with the weight-for-age targets outlined by Troccon et al. (1993), which are based on their expected mature BW. It has not been determined if the targets outlined by Troccon et al. (1993) are suitable for pasture-based heifers or those reared under different management strategies within a pasture-based system.

4.5.1 Target Weights

Weight-for-age targets (Troccon, 1993) have long provided a benchmark for the growth of replacement heifers. They have, however, been designed to ensure that heifers are grown at a constant rate throughout the rearing period and, as a consequence, will attain puberty, become pregnant, and calve as soon as possible, thus minimizing the non-productive period (Costa et al., 2021). As such, the growth trajectory of the heifer is often described as linear (Silva et al., 2021). Consistent with Handcock et al. (2019b), the data in the present study demonstrate that pasture-based heifer growth is not linear. This may be because growth is limited by both the quality and quantity of pasture (Waghorn and Clark, 2004), and as such, follows a seasonal pattern (Handcock et al., 2021). The growth trajectory of pasture-based heifers in the present study was consistent with that of two sigmoidal curves joined by a plateau in the middle that corresponded to the over-winter period. The transition from grazing pasture to winter housing involves a period of dietary adjustment and acclimatization to the shed (O'Driscoll et al., 2009); therefore, it is unsurprising that the heifer's growth is disrupted slightly.

Previous research advises that heifers should be 30, 60, and 90% of mature BW at six, 15, and 24 months respectively, it is, however, conceivable that pasture-based heifers would require different weight-for-age targets due to their seasonal pattern of growth (Handcock et al., 2019b). The equation proposed in the present study agrees with these targets but also allows for the generation of weight-for-age targets at any time point throughout the rearing period. For example, the creation of additional targets for pasture-based winter-housed heifers at housing and turnout to grass, i.e., when the farmer may be more likely to weigh animals, may optimize heifer management during the over-winter period. If heifers are below target when housed for winter, and if silage quality is suboptimal, concentrate supplementation may be required to ensure heifers are on track for breeding (Kennedy et al., 2013). Similarly, if heifers are ahead of or behind target weight at turn out to pasture, grassland management may be adjusted accordingly. Additional targets will be of particular benefit to pasture-based heifers that are reared off the milking platform and may not be regularly monitored. With the correct management, existing weight-for-age targets are achievable for pasture-based dairy heifers; heifers that achieve targets will have improved reproduction (Handcock et al., 2020), milk production (McNaughton and Lopdell, 2013; Martín et al., 2020), and longevity (Handcock et al., 2020), therefore achieving targets is of practical significance for farm profit (Boulton et al., 2017).As is evident from both the present study and previous research (McNaughton and Lopdell, 2012; Handcock et al., 2016; Martín et al., 2020), there is considerable variation in heifer BW, and as such, it is important that, when making decisions, all animals in the herd are accounted for (Handcock et al., 2016). Therefore, it is appropriate that the BW prediction equation in the present study was created using the BW data of heifers reared under different management systems. Furthermore, the predicted mature BW (i.e., the asymptote of the curve; Taylor and Fitzhugh, 1971) of the HF heifers in the present study (573 kg) was consistent with that reported by Evers et al. (2021) in a study of 80 commercial dairy farms around Ireland where the average BW of third, fourth and fifth lactation HF animals was 576 kg. This indicates that the growth trajectory described in the present study is representative of that of pasture-based dairy heifers in Ireland. The BW of HF and JE were significantly different throughout the rearing period; stratifying the data by breed group increased the predictive power of the equation; the RMSE was reduced by 7.6 (from 33.6 to 26 kg) and 14.5 kg (from 33.6 to 19.1 kg) for HF and JE respectively, while the R^2 was increased from 0.95 to 0.97. The equations proposed in the present study to predict the BW of HF and JE heifers had RMSE of 4 and 7 kg higher than that reported by Kuhi et al. (2019). However, the equations proposed by Kuhi et al. (2019) were created using the median monthly BW of heifers reared in the United States, and as such, variation in individual BW was minimized.

4.5.2 Effect of Treatment on Weight

Pasture-based dairy heifers may require different rearing strategies to ensure that their potential is realized (Handcock et al., 2019a). Strategies that, for example, increase the length of the milk-feeding period to take advantage of high FCE in early life (Meale et al., 2015) or increase the proportion of good quality grazed grass in the diet (Patterson et al., 2018), may be used to optimize heifer BW gain. Throughout the rearing period, the 12wH heifers in the present study had superior BW and, consequently, the greatest attainment of target weights as defined by Troccan (1993), which has been reported to benefit future lactation performance of the heifer (Soberon et al., 2012b). However, a higher proportion of the 12wH heifers were also >5% ahead of target at six (17.0%), 15 (12.5%), and particularly 24 months (62.5%), which may be to the detriment of reproductive efficiency as mature cows (Archbold et al., 2012) and calving performance (Mee et al., 2011). This method of rearing heifers is also costly as it involves extending the length of the milk-feeding period, which is the most expensive aspect of a heifer rearing program (Boulton et al., 2017), and also involves feeding high levels of expensive concentrates (Finneran et al., 2010). Furthermore, if fertility and calving performances are negatively affected by this intensive feeding/rearing strategy, the timeframe in which heifer rearing costs are repaid will be extended (Tozer and Heinrichs, 2001). Less intensive rearing strategies, such as a shorter milk-feeding period and feeding less concentrate and pasture (Boulton et al., 2017), may minimize heifer rearing costs. This method of rearing was investigated in the present study by weaning calves at eight weeks of age and subsequently offering them a low post-weaning feeding regime (8wL). Although reducing the length of the milk-feeding period will inevitably result in a lighter BW at weaning (de Passillé et al., 2011), in the present study, by 11 months, there was no effect of weaning age (8w or 12 w). This was consistent with previous research whereby the BW advantage of later-weaned calves disappeared shortly after weaning (de Passillé et al., 2011; Dennis et al., 2019). Nevertheless, compared to 8wH and 12wL, a higher proportion of 8wL heifers were ± 5% of target weight at six and 15 months. Less intensive heifer rearing strategies may therefore be utilized to reduce the cost of heifer rearing on dairy farms (Boulton et al., 2017) as there is no long-lasting impact on growth, though further research may be required to ensure there are no repercussions in terms of milk production potential (Soberon et al., 2012b) and reproductive efficiency (Archbold et al., 2012).

4.5.3 Breed

It is widely accepted that HF and JE animals differ in terms of BW (Prendiville et al., 2009; Handcock et al., 2019b), and this claim is corroborated by the present study whereby HF heifers were heavier than JE heifers at each time-point in the rearing period. Therefore, it is expected that HF and JE would exhibit different growth trajectories in the rearing period (Handcock et al., 2019b). Although the HF and JE in the present study grew at different rates having an ADG of approximately 0.71 and 0.55 kg/heifer/day, respectively, in the period from one to 11 months, their growth trajectories followed a similar pattern. Previous research reported that JE heifers were better able to achieve weight-for-age targets in pasture-based rearing systems than HF (McNaughton and Lopdell, 2013), and as such, it was advised that breed be considered in the formulation of target BW (Handcock et al., 2019b). In the present study, a lower proportion of JE (40.4%) were at or ahead of target BW at six months of age compared to HF (51.9%); however, a higher proportion of JE attained target weight at 15 months (48.3 and 46.5% for JE and HF, respectively). Failing to achieve target BW, particularly at 15 months, may be detrimental to fertility performance (Macdonald et al., 2005) and first lactation milk production (Martín et al., 2020). Handcock et al. (2019b) reported that JE had higher growth rates just prior to calving, which is consistent with the present study whereby a higher proportion of JE were either at or ahead of target weight at 24 months compared to HF (91.4 and 85.3% for JE and HF, respectively). This suggests that JE are an early maturing breed (Freer et al., 2007; Handcock et al., 2019b), and as such, feed management of the in-calf heifer may need modification to ensure they do not become over-fat prior to calving (Sieber et al., 1989).

4.6 Conclusion

Although current weight-for-age targets require steady growth throughout the rearing period, seasonal constraints dictate that pasture-based heifer growth is not linear; it instead follows a sigmoidal pattern. The findings in the present study show that, with correct management, current weight-for-age targets are achievable under a variety of heifer rearing strategies. However, using the proposed equation to create additional targets will provide pasture-based farmers with a benchmark for bodyweight at times when they may be more likely to weigh their heifers, for example, housing and turnout. Nevertheless, subsequent milk production must be evaluated to ensure that there are no effects of heifer rearing strategy on performance in the lactating herd.

Chapter 5: The Effect of Weaning Age and Post-Weaning Feeding Rate on Growth and Fertility of Pasture-Based Holstein-Friesian and Jersey Dairy Heifers

Livestock Science (Submitted)

5.1 Abstract

Achieving weight-for-age targets while rearing heifers is essential for future productivity, particularly in pasture-based production systems where the growth trajectory is not linear. The present study investigated the effect of weaning age (eight or 12 weeks) and post-weaning feeding regime (high or low) on the growth and fertility performance of pasture-based HF (n=130) and JE (n=57) dairy heifers over two years. Body weight and LBM of the heifers were monitored from birth until breeding.

Fertility performance was also observed. At three months of age, the 12-week weaned calves were superior in terms of BW and LBM; however, this advantage had disappeared entirely by nine months of age. There was an interaction between pre and post-weaning treatment for length at three, six, and nine months, respectively, indicating a different mechanism in the pattern of linear growth compared with BW. Body weight, ADG, and LBM were significantly different for HF and JE heifers throughout the experiment. The 12w heifers were more likely to exhibit pre-breeding estrus activity when compared to their 8w herd mates. There were significant interactions between weaning age and post-weaning growth rate for days from conception to MSD, pregnancy to the first service, pregnant to first service, and 42-day pregnancy rate, respectively, such that 8wL heifers and 12wH heifers had improved fertility performance relative to their 8wH and 12wL herd mates. There was an effect of breed on the six-week in-calf rate, such that JE heifers were less likely to fall pregnant in the first six weeks of the breeding season.

5.2 Introduction

Achieving heifer weight for age targets (Patterson et al., 1992) throughout the rearing period is necessary so that replacement heifers, particularly in seasonal calving systems, achieve puberty and are available for breeding at 15 months (McNaughton and Lopdell, 2013). This minimizes the non-productive lifespan of the heifer and maintains a compact seasonal calving pattern (Wathes et al., 2014). Many farmers are interested in early weaning strategies in an effort to reduce both costs and labour requirements, particularly in seasonal calving systems. Substantial costs are incurred in the pre-weaning period; a UK survey determined that it cost on average £195 to rear a calf from birth until weaning at 62 days, with milk-feeding accounting for 37.3% of these costs (Boulton et al., 2015). However, calves are most efficient at converting nutrients to BW gain in early life (Kertz et al., 1998) and, therefore, may benefit from high feeding rates in the pre-weaning period. Some studies have determined that intensified feeding in the pre-weaning period, either by increasing the volume of milk-fed (Hill et al., 2009), altering milk composition (Terre et al., 2009) or lengthening the duration of milk-feeding (Bjorklund et al., 2013), may have positive associations with age and BW at breeding.

Similarly, higher feeding rates in the post-weaning period have been found to increase BW and thus reduce the age at puberty (Pereira et al., 2017; Le Cozler et al., 2019). Feeding energy-dense diets in the post-weaning period may result in heifers that are younger and lighter at the onset of puberty (Rincker et al., 2011). Feeding in the pre (Khan et al., 2011) and post-weaning (Pereira et al., 2017) periods are therefore a function of age at breeding and so should be optimized by meeting weight-for-age targets (Patterson et al., 1992; Wathes et al., 2014).

To date, there are few studies that have examined the effect of both pre and post-weaning nutrition on growth and fertility performance throughout the first 15 months of the rearing period. The objective of the present study, therefore, was to determine the effect of weaning age and post-weaning feeding regime on BW, ADG, and LBM, taken from birth to breeding for both HF and JE dairy heifers to determine if there is a relationship between BW, ADG, LBM and fertility parameters. It was hypothesized that later weaned heifers offered a high post-weaning feeding regime would be heavier, longer, taller, have greater girth circumference, and ultimately have improved fertility than their herd mates weaned earlier and offered a low post-weaning feeding regime.

5.3 Materials and Methods

This study was carried out on the Dairygold Research Farm at Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Kilworth, Co. Cork, Ireland (52°09′N 8°16′W) between February 2018 and September 2020. Ethical approval was granted by the Teagasc Animal Ethics Committee (TAEC) (TAEC129/2016), and procedure authorization was granted by the Irish Health Products Regulatory Authority (HPRA) (AE19132/P070). All experiments were conducted in accordance with the Cruelty to Animals Act (Ireland 1876, as amended by European Communities Regulations 2002 and 2005) and the European Community Directive 86/609/EC.

5.3.1 Experimental Treatments and Animals

The study examined 2 (weaning ages; 8w or 12w) x 2 (post-weaning planes of nutrition; (H or L) in a factorial design, with a total of 187 heifer calves assigned to the study (Figure 5.1). Heifers enrolled in the study were born across two years; in 2018 (n=26 JE heifers with a mean bBW of 23.0 ± 2.38 kg and n=62 HF heifers with a mean bBW of 34.4 ± 4.67 kg) and in 2019, there were 31 JE heifers with a mean bBW 24.5 ± 2.88 kg and 68

HF heifers with a mean bBW 35.2 ± 4.23 kg. The heifers born in 2018 (9 February ± 12.8 days) and 2019 (8 February ± 12.7 days) will henceforth be referred to as Y1 and Y2, respectively. Calves were balanced for bBW, breed, and date of birth and were randomly assigned to their treatment.

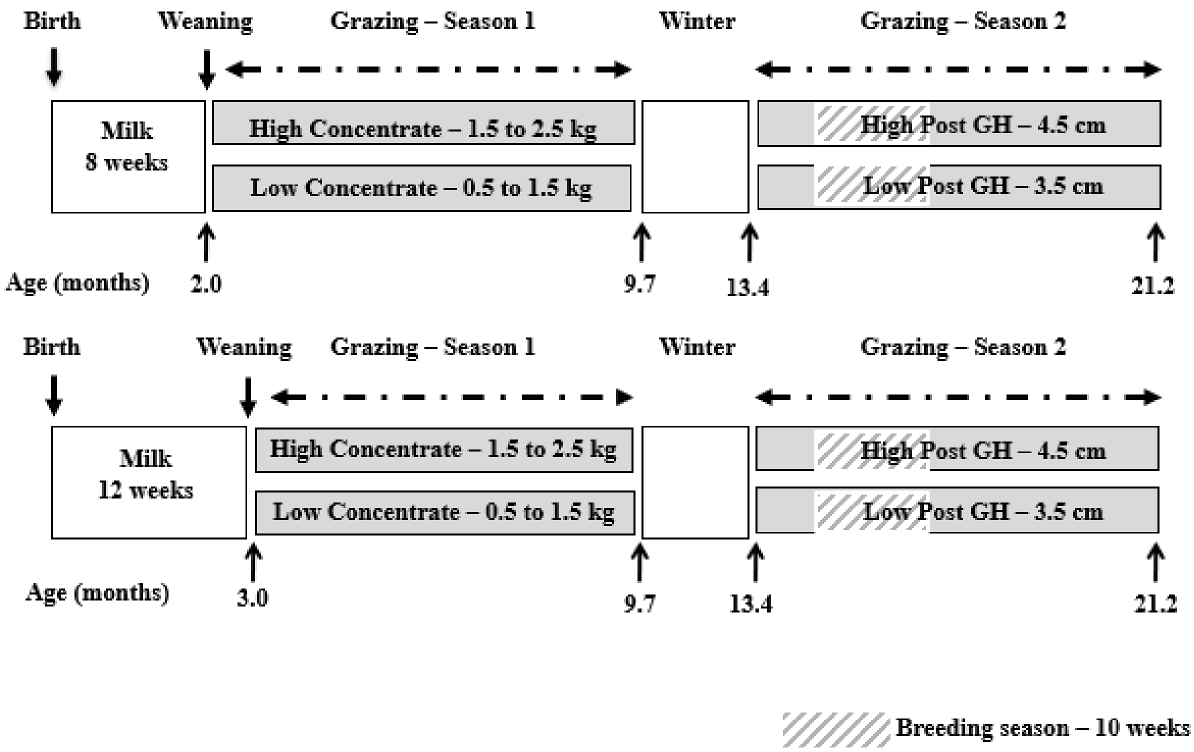


Figure 5.1: Illustration of the experimental design, timeline, and the approximate age (months) of the heifers at each period.

5.3.2 Pre-Weaning Heifer Management

5.3.2.1 Colostrum and Transition Milk Feeding

Trained and experienced personnel supervised all calving events. Following birth, calves were immediately removed from their dam as a standard biosecurity measure. Each calf was weighed (TruTest XR3000, Tru-test Limited, Auckland, New Zealand), and 10% iodine spray was applied to the navel area.

Calves were then placed in straw-bedded individual pens (1.3 x 0.8m), located indoors, and received three litres of good quality colostrum from a single dam, not necessarily their mother (Barry, 2020), within two hours of birth. The colostrum (first milk produced by the cow post-calving) was collected from freshly calved cows twice per day at scheduled milking times (07:30h or 15:00h). Colostrum was tested using a digital refractometer (Hanna Instruments, HI-96801 Refractometer, Hanna Instruments Limited, Bedfordshire, United Kingdom), and only colostrum with a Brix value of ≥22% was retained and fed as the first feed (Bielmann et al., 2010). Following collection and quality testing, colostrum was immediately refrigerated at 4ºC for a maximum of 48 hours (Cummins et al., 2017) before being warmed to 37ºC in a tepid water bath prior to feeding. After colostrum feeding, calves received five feeds of transition milk (2 Litres per feed; Brix value <22%) while still located in individual pens.

5.3.2.2 Pre-Weaning Period

When the calves had received all of their colostrum and transition milk feeds (approximately three days old), they were grouped by age, irrespective of treatment, in a group pen containing approximately 20 calves. The group pens, which were indoors, measured 9.5 x 4.8m and consisted of a concrete feeding area with a straw-bedded lie back. They remained in the same group pen until they were weaned. In the group pen, calves were offered 26% CP MR (Volac Heiferlac; Volac, Church St, Portaliff Glebe, Killashandra, Co. Cavan; 26% CP, 16% crude oils and fats, 7% crude ash) at a reconstitution rate of 15% (150g MR/L water) from an automatic feeder (Vario Smart Powder, TAP5–VS1–50: Förster–Technik GmbH, Gerwigstrasse 25, D – 78234 Engen, Germany). When calves were introduced to the feeder initially, they were offered 4 L/MR/day, however; this was gradually increased to 6 L/MR/day over the first seven days. This volume of MR remained constant at 6 L/MR/day until eight days before each calf reached their respective weaning age (eight or 12 weeks) such that in the pre-weaning period, the eight and 12-week weaned calves were offered on average 49.4 and 74.6 kg of MR, respectively. At which point, they were gradually weaned over a period of seven days. At all stages of the feeding program, the daily milk allowance was delivered in three equal feeds prepared freshly at 37 ºC in one-litre portions. During the housing period, fresh, clean drinking water was available at all times, while straw and concentrates (Sweet Start Calf Pencils, Southern Milling Ltd, Marina Mills, Cork; 20% CP, 7.2% crude fibre, and 9.2% ash) were offered *ad libitum*.

5.3.3 Post-Weaning Heifer Management

5.3.3.1 First Grazing Season

When all calves had been weaned, they were regrouped according to their post-weaning treatment group (H or L) and rotationally-grazed predominantly perennial ryegrass swards (>80%) until they were housed the following winter. The H and L heifers were grazed adjacent to one another, separated by a temporary electric fence, to ensure grass of similar quality was offered. Differences between the treatments were created by feeding differing levels of concentrates (Dairygold Beeflav, Dairygold Co-Operative Society Ltd, Lombardstown Mill, Mallow, Co. Cork; 16% CP, 10% crude fibre, and 5.9% ash). Calves assigned to H post-weaning treatment were offered 1.5-2.5 kg concentrate/heifer/day, with heifers assigned to the L treatment offered 0.5-1.5 kg concentrate/heifer/day. Supplementation depended on grass quality and availability.

5.3.3.2 Over-Winter Management

Over-winter management was similar for treatments within year of birth. For the first three weeks of winter treatment, Y1 (30th November - 17th December) and Y2 heifers

(25th November – 18th December) were offered Red Start (a kale and rape hybrid forage crop), which was grazed *in-situ*, in addition to *ad-libitum* hay and 1 kg concentrates/heifer/day (Dairygold Beeflav, Dairygold Co-Operative Society Ltd, Lombardstown Mill, Mallow, Co. Cork; 16% CP, 10% crude fibre and 5.9% ash). Subsequent to this, heifers were housed, and grass silage (64-67% DMD) and 1.5-2 kg concentrate/heifer/day were offered (Roche's Feeds Heifer Rearer 20%; Roches feeds, Dock Road, Co. Limerick; 20% CP). Total over-winter concentrate supplementation was the same for all heifers. For the final six weeks of the over-winter period, Y1 (7th February – 19th March) and Y2 (4th February – 18th March) heifers were turned out and offered forage crop (Red Start, as described above), *ad-libitum* hay, and 1 kg concentrate/heifer/day before being re-grouped by post-weaning treatment and turned out to grass for their second grazing season.

5.3.3.3 Second Grazing Season

In their second grazing season, Y1 (March 19 –November 25) and Y2 (March 18 – October 22), heifers were re-grouped by treatment (H or L) and offered an all-grass diet. Contrasting pasture allowances were offered to create differences between the treatments. A post-grazing height (rising plate meter; Jenquip, Feilding, New Zealand) of 4.5 cm was targeted for the H treatment, while 3.5 cm was the target for the L treatment.

5.3.4 Grassland Management

The farm was walked weekly to estimate the quantity of pasture available in each paddock (kg DM/ha), and data were recorded in PastureBase Ireland (PBI; Hanrahan et al., 2017). The grass wedge decision support tool, which was generated in PBI from each weekly walk, aided the selection of the next most suitable paddock for grazing based on the pasture available (pre-grazing yield). The target pre-grazing yield was 1,600 kg DM/ha

(> 4 cm). The wedge also helped identify paddocks where the pre-grazing yield was too high (>1800 kg DM/ha), and these paddocks were mown and the surplus grass removed as silage.

Similarly, deficits were identified using the grass wedge, and concentrate supplementation was adjusted accordingly until sufficient pasture was available to reduce concentrate supplementation levels (i.e., grass growth equalled or exceeded demand). Fresh grass (>4 cm) was allocated to both (H and L) grazing groups every two to three days. Each grass allocation area (m^2) was measured using a trundle wheel (DW-PRO; Caulfield Industrial Ltd., Oranmore Business Park, Oranmore, Co. Galway). Fresh, clean drinking water was continuously offered.

5.3.5 Animal Measurements

5.3.5.1 Body weight

Body weight was measured at birth and every two weeks thereafter until nine months of age, after which it was measured monthly until breeding at 15 months (TruTest XR 3000, Tru-test Limited, Auckland, New Zealand). The weighing scales were calibrated prior to use. Average daily gain was calculated by regressing BW measurements over the trial period.

5.3.5.2 Linear Body Measurements

Linear body measurements (BL, WH, and HG) were recorded twice a month from birth until nine months and every three months thereafter until breeding at 15 months. All measures were recorded in centimetres. The same person consistently took measurements to minimize variation. A soft measuring tape (Whitecroft Essentials Ltd 2018, Mitcheldean, Gloucestershire) was used to measure the BL and HG. In order to ensure the tape was measuring correctly (i.e., it had not stretched over time), it was tested against a measuring stick before each use. Body length was defined as the horizontal distance from the top of the withers to the ischium. Heart girth was defined as the circumference of the animal's body measured directly behind the front legs. A specialized measuring stick (Nasco, Fort Atkinson, WI), which accurately measured the WH by lowering a sliding crossbar, was used. Withers height of the animal was defined as the vertical distance from the ground to the top of the withers.

5.3.6 Fertility

The Y1 heifers were examined using trans-rectal ultrasonography (Ibex Pro scanner with an 8.5 MHz transducer, E.I. Medical Imaging, Loveland, CO) one month before MSD to determine if they had started ovulating. In 2020, restrictions due to the global SARS-CoV-2 pandemic meant that pre-breeding scanning was not possible. Instead, Y2 heifers were tail painted one month prior to the commencement of the breeding season. Heifers were visually observed twice per day for one month; if physical signs of estrus were displayed or if the tail paint was found to have been removed (Palmer et al., 2010), it was determined that the heifer had started ovulating.

The breeding season for Y1 and Y2 heifers began on April 29, 2019, and April 27, 2020, respectively, and lasted for ten weeks. In accordance with best practice reproductive management (Berry et al., 2015), heifers detected in estrus were inseminated once daily, at midday, by the same technician. For the first seven days of the breeding season Y1 and Y2 heifers that were observed standing to be mounted, that had tail paint removed or displayed physical signs of estrus were drafted for AI with frozen-thawed semen from a bull, chosen from a team of 12 (six JE and six HF) and 15 (five JE and ten HF) genomically selected sires of the highest EBI in Y1 and Y2, respectively. The team of bulls was evenly distributed across each treatment group.

After seven days, heifers that had not submitted to AI were identified and administered two ml of an intramuscular prostaglandin injection (Estrumate®; Intervet, Dublin, Ireland) to induce estrus (Sprott and Carpenter, 2007). Once all heifers had been AI'd, a team of four easy-calving Aberdeen Angus stock bulls carried out natural service. Two stock bulls were placed at random with each treatment group. Pregnancy status was determined by transrectal ultrasound on average 40 days and again 100 days post-insemination. The ultrasound examination records were used to predict a calving date for each heifer.

The following reproductive measurements were recorded: achievement of puberty prior to breeding, days to conception from MSD, submission rate, pregnancy rate to the first service, 42-day pregnancy rate, pregnancy result, and AFC. The pre-breeding scan result took account of whether or not the animal had started ovulating prior to MSD. The days to conception from MSD was defined as the number of days taken for a heifer to conceive after MSD. The submission rate was defined as the number of days from MSD to the first insemination. The pregnancy rate to the first service was defined as the proportion of heifers pregnant to the first service as confirmed by an ultrasound scan at the end of the breeding season. The 42-day pregnancy rate was defined as whether or not the animal became pregnant in the first six weeks of the breeding season. Age at first calving was defined as the age in days at which a heifer calved for the first time.

5.3.7 Data Editing

In order to determine if BW at breeding had a significant effect on fertility performance, HF and JE heifers were also stratified by BW at breeding: heifers were separated into three groups based on whether or not they were below, at, or ahead of target BW at breeding for their breed group. Target BW at breeding was defined as approximately 60% of mature BW (Patterson et al., 1992). The threshold BW values delineating the different strata for the HF heifers were ≤315 kg, between 316 kg and 335 kg, and ≥336 kg at breeding. The threshold BW values delineating the different strata for the JE heifers were ≤235 kg, between 236 kg and 255 kg, and ≥256 kg at breeding.

5.3.8 Statistical Analysis

Statistical analyses were conducted using SAS (version 9.4; SAS Institute Inc., Cary, NC). Body weight and LBM were assessed using linear mixed models in PROC MIXED. Factors considered in the model investigating BW and LBM were pre and post-weaning treatment, the interaction between pre and post-weaning treatment, breed, and birth year. Birth BW was included in the models as a covariate. In addition, the EBI sub-index for beef carcass, which would account for genetic variation in body size, was also included in the model for LBM as a covariate. Significant associations were confirmed when $P < 0.05$ and least-square means were assessed.

Continuous fertility variables such as submission rate to AI, MSD to conception interval, and AFC were also analysed using linear mixed models in PROC MIXED. Factors considered in the model investigating continuous fertility variables were pre and post-weaning treatment, the interaction between pre and post-weaning treatment, breed, the month in which the heifer was born, and birth year. In the linear mixed models to determine if BW at breeding affected continuous fertility variables, factors considered in the model were breed nested within strata for BW at breeding and year of birth. Significant associations were confirmed when P < 0.05 and least-square means were assessed.

Binary fertility variables such as pre-breeding scan result, whether or not the heifer became pregnant to her first service, 42-day pregnancy rate, and whether or not the heifer achieved a positive pregnancy result were analysed using PROC GLIMMIX (binomial distribution and link logit functions). Factors considered in the model investigating continuous fertility variables were pre and post-weaning treatment, the interaction between pre and post-weaning treatment, breed, month in which the heifer was born, and year of birth.

In the models to determine if BW at breeding had an effect on binary fertility variables, year of birth was included as a covariate. Factors considered in the model investigating binary fertility variables were breed nested within strata for BW at breeding. Significant associations were confirmed when P < 0.05 and least-square means were assessed. The PROC GLIMMIX model for whether or not the heifer achieved a positive pregnancy result did not converge due to the distribution of data, such that all the 8wL heifers achieved a positive pregnancy result. Consequently, the pregnancy rates (%) for each of the treatment groups are instead presented.

5.4 Results

5.4.1 Growth and Linear Body Measurements

The associations between weaning age, post-weaning feeding regime, and breed with BW, ADG, BL, HG, and WH, respectively, are outlined in Table 5.1. There was a significant interaction between weaning age and post-weaning feeding regime for BL at three (P = 0.016), six (P = 0.016), and nine (P = 0.009) months of age, respectively. There was no significant interaction between weaning age and post-weaning feeding regime for any of the other variables measured, and therefore, only the main effects of weaning age, post-weaning feeding regime, and breed are detailed in the text.

Average daily gain from birth until three months old was significantly higher (P = <0.001) for 12w calves compared to 8w calves (0.62 and 0.54 kg/day, respectively). Calves weaned at 12 weeks had significantly (<0.001) higher BW, BL, HG, and WH than their 8w herd mates at three months of age. Neither weaning age nor post-weaning feeding regime was associated with the ADG of the calves from three to six months; however, the relationship between BW and weaning age tended towards significance (P = 0.051).

Table 5.1: Effect of weaning age (Pre), post-weaning treatment (Post), the interaction between Pre*Post, and breed on body weight (BW; kg), average daily gain (ADG; kg/heifer/day),length (cm), girth (cm) and height (cm) of Jersey (JE) and Holstein-Friesian (HF) dairy heifers at key time points during the rearing period.

	Treatment					Breed			Pr > F			
	8 weeks		12 weeks									
	High	Low	High	Low	S.E	HF	JE	S.E	Pre	Post	Pre*post	Breed
3 months												
BW	74.0	74.7	82.2	79.9	1.34	87.3	68.1	0.99	<0.001	0.548	0.263	<0.001
ADG birth to 3 months	0.54	0.54	0.64	0.60	0.017	0.63	0.53	0.012	<0.001	0.346	0.287	<0.001
Length	72.2	73.4	74.7	73.6	0.52	75.9	71.1	0.66	0.003	0.961	0.016	0.001
Girth	102.8	102.5	105.2	103.5	0.82	108.0	99.0	1.05	0.018	0.180	0.347	<0.001
Height	86.0	85.8	87.5	87.6	0.54	89.8	83.7	0.68	0.006	0.900	0.856	<0.001
6 months												
BW	127.6	130.2	136.2	130.9	2.43	149	113.5	1.8	0.051	0.581	0.101	<0.001
ADG 3 to 6 months	0.64	0.66	0.64	0.61	0.017	0.73	0.55	0.017	0.316	0.773	0.227	<0.001
Length	81.7	82.9	83.8	82.7	0.52	84.8	80.8	0.66	0.040	0.871	0.016	0.002
Girth	122.1	122.7	124.3	122.7	0.81	127.4	118.5	1.03	0.120	0.538	0.122	<0.001
Height	95.9	96.4	98.0	97.0	0.54	100.4	93.3	0.69	0.005	0.669	0.117	<0.001
9 months												
BW	195.2	185.0	204.0	183.3	3.13	216	168.1	2.309	0.246	<0.001	0.090	<0.001
ADG 6 to 9 months	0.81	0.66	0.80	0.62	0.025	0.79	0.65	0.018	0.353	<0.001	0.510	<0.001
Length	94.9	95.0	96.5	94.2	0.52	97.4	92.9	0.659	0.464	0.0165	0.009	0.003
Girth	141.0	139.4	143.6	139.2	0.94	145.4	136.2	1.2	0.154	0.004	0.102	<0.001
Height	107.4	106.5	108.6	106.6	0.56	109.6	105.0	0.71	0.213	0.003	0.275	0.006
12 months												
BW	229.9	222.3	238.8	216.7	3.44	254	200	2.531	0.643	<0.001	0.033	<0.001
ADG 9 to 12 months	0.42	0.45	0.41	0.40	0.020	0.45	0.38	0.015	0.187	0.503	0.358	0.001
Length	103.9	103.9	104.8	103.3	0.51	105.4	102.5	0.654	0.813	0.117	0.088	0.018
Girth	153.3	150.4	154.7	151.0	0.98	156.5	148.2	1.243	0.253	0.002	0.653	0.005
Height	113.0	111.9	114.5	112.0	0.56	115.9	109.9	0.707	0.116	0.000	0.164	<0.001
15 months												
BW	273.0	267.9	280.1	265.3	3.65	304	238.8	2.688	0.539	0.006	0.175	<0.001
ADG 12 to 15 months	0.51	0.54	0.49	0.58	0.018	0.60	0.46	0.013	0.610	0.007	0.105	<0.001
Length	108.6	108.8	109.3	108.3	0.48	110.0	107.5	0.608	0.826	0.295	0.133	0.031
Girth	162.6	159.3	164.5	160.2	0.93	166.2	157.0	1.181	0.095	<0.001	0.553	<0.001
Height	117.6	116.7	118.1	116.6	0.55	120.1	114.5	0.704	0.683	0.015	0.559	<0.001

At six months of age, there was still an effect of weaning age on BL (82.3 and 83.3 cm for 8w and 12w, respectively) and WH (96.2 and 97.5 cm for 8w and 12w, respectively). There was no effect of weaning age at nine months of age, and instead, post-weaning treatment positively influenced all measured growth performance variables (P<0.003). Post-weaning feeding regime had no effect on ADG from nine to 12 months or length at 12 months; however, BW (234.4 and 219.5 kg for H and L, respectively), HG (154.0 and 150.7 cm for H and L, respectively), and WH (113.8 and 112.0 for H and L, respectively) were still significantly higher for H calves. Similarly, at 15 months, the post-weaning feeding regime had a significant effect on all growth parameters with the exception of BL (109.0 and 108.6 for H and L, respectively). Body weight, ADG, BL, HG, and WH were significantly different for HF and JE at each time-point during the experiment.

5.4.2 Fertility Performance

The associations between weaning age, post-weaning feeding regime, breed, and the likelihood of pre-breeding estrus activity, whether a heifer needed one or more than one service to achieve pregnancy, whether a heifer was confirmed pregnant or not, whether a heifer became pregnant to her first service or not and whether a heifer became pregnant in the first 42 days of the breeding season are outlined in Table 5.2. The 12wH and L heifers were more likely to exhibit pre-breeding estrus activity when compared to their 8w weaned herd mates (odds ratio (OR) = 1.00 and OR = 0.70, respectively). The associations between post-weaning treatment (P=0.093) and the interaction between pre and post-weaning treatment (P=0.051) for the number of services required to achieve pregnancy, respectively, were tending towards significance.

Table 5.2: Associations between weaning age (Pre), post weaning feeding regime (Post) and breed, and the interaction between Pre*Post for a fertility performance

			Pr > F			
	OR†	95% CI†	Pre	Post	Pre*post	Breed
(a) Pre-breeding estrus activity						
Pre*Post						
12 weeks high	1		0.041	0.680	0.555	0.28
12 weeks low	0.7	0.242 - 2.023				
8 weeks high	0.39	0.142 - 1.069				
8 weeks low	0.416	0.150 - 1.149				
Breed						
HF	1					
JE	1.546	0.696 - 3.434				
(b) Number of services						
Pre*Post						
12 weeks high	1		0.604	0.093	0.051	0.502
12 weeks low	3.003	1.282 - 7.035				
8 weeks high	2.112	0.921 - 4.844				
8 weeks low	1.943	0.842 - 4.486				
Breed						
HF	1					
JE	0.802	0.421 - 1.531				
(c) Pregnant to first service						
Pre*Post						
12 weeks high	1		0.877	0.601	0.010	0.719
12 weeks low	0.52	0.222 - 1.221				
8 weeks high	0.464	0.199 - 1.081				
8 weeks low	1.235	0.498 - 3.062				
Breed						
HF	1					
JE	1.13	0.579 - 2.208				
(d) 42-day pregnancy rate						
Pre*Post						
12 weeks high	1		0.417	0.855	0.023	0.045
12 weeks low	0.361	0.107 - 1.217				
8 weeks high	0.488	0.14 - 1.702				
8 weeks low	1.608	0.347 - 7.458				
Breed						
HF	1					
JE	0.4	0.163 - 0.979				

† OR = odds ratio, CI = confidence interval

§ Approaching significance (P < 0·10)

There were significant associations (P=0.007) between weaning age and post-weaning feeding regime for days from MSD to conception (Table 5.3); the 8wL and 12wH heifers (15.8 ± 2.9 days and 18.0 ± 2.8 days, respectively) had fewer days from MSD to conception compared to the 8wH and 12wL heifers (24.1 ± 2.76 days and 23.3 ± 2.82 days, respectively). There was a significant interaction between weaning age and post-weaning feeding regime for pregnancy to first service such that the 12wH (69%) and 8wL (74%) heifers achieved a higher pregnancy rate to first service relative to their 12wL (54%) and 8wH (52%) herd mates. There was a significant interaction between weaning age and post-weaning feeding regime for the 42-day pregnancy rate: the 8wL heifers were more likely to achieve a positive pregnancy result in the first six weeks of the breeding season when compared to the 12wL heifers. Pregnancy rates were different between treatment groups such that 100.0, 91.7, 93.5, and 87.8% of the 8wL, 8wH, 12wL, and 12wH heifers, respectively, were pregnant.

Jersey heifers were less likely to become pregnant in the first 42 days of the breeding season (OR = 0.400; Table 5.2) than the reference breed (HF). When the heifers were stratified by breed and BW at breeding, whether they were ahead of target, at target or below target BW, did not affect the likelihood of pre-breeding estrus activity, whether a heifer needed one or more than one service to achieve pregnancy, whether a heifer was confirmed pregnant or not, whether a heifer became pregnant to her first service or not or the 42-day pregnancy rate. Despite the model being corrected for age at MSD, when heifers were recategorized by breed and BW at breeding, there was a tendency for the HF and JE heifers that were overweight at breeding (≥ 336 and ≥ 256 kg, respectively) to be (P = 0.086) older at first calving, whereas heifers that were at and below target BW, respectively, were younger at first calving (Table 5.4).

Table 5.3: Effect of treatment (weaning age and post-weaning feeding regime) and breed on expected age at first calving (AFC; days), days to conception from MSD and submission rate (days).

	Treatment					Breed			Pr > F			
	8 weeks		12 weeks		SEM	HF	JE	SEM	Pre	Post	Pre*post	Breed
	High	Low	High	Low								
Expected AFC	741.8	734.9	739.6	740.4	2.68	739.1	739.3	2.12	0.503	0.204	0.111	0.928
Days to conception from MSD	24.1	15.8	18.0	23.3	2.80	19.4	21.2	2.23	0.779	0.551	0.007	0.509
Submission rate	8.9	7.4	7.5	8.4	0.69	7.8	8.3	0.55	0.709	0.654	0.053	0.489

Table 5.4: Effect of BW at breeding and breed on expected AFC (days), days to conception from MSD (days) and submission rate (days)

	HF					JE				
	≤ 315 kg	316-335 kg	≥ 336 kg	SEM	Pr > F	≤ 235 kg	236-255 kg	≥ 256 kg	SEM	Pr > F
Expected AFC	739.0	736.0	744.8	2.84	0.086	734.0	738.8	744.1	4.63	0.086
Days to conception from MSD	18.8	14.6	18.8	2.69	0.505	13.8	21.5	20.7	4.07	0.505
Submission rate	8.0	7.8	7.3	0.66	0.587	9.6	7.5	7.5	1.00	0.699

5.5 Discussion

5.5.1 Growth and Linear Body Measurements

There is currently no definitive heifer rearing strategy that optimizes both growth and fertility performance of dairy heifers in a pasture-based production system.

The present study determined that a four week increase in weaning age resulted in advantages in live-weight and frame size at 12 weeks of age. The 12w calves achieved superior ADG from birth to three months due to the additional MR consumed relative to their 8w herd mates. Increasing the length of the milk-feeding period is widely recognized as a useful management tool to increase live-weight by taking advantage of high feed conversion efficiency in early life (De Passillé et al., 2011; Eckert et al., 2015). Linear body measurements were found to be highly correlated with live-weight in the present study, and therefore it is unsurprising that there is a significant relationship between treatment and length, girth, and height, respectively, at three months of age. From three to six months of age ADG was not significantly different between treatment groups: this is because post-weaning treatment was not implemented until 1st of June (calves were on average 3.7 months of age) in Y1 and Y2 when all calves had been weaned off milk. During this time, the calves underwent a period of dietary adjustment, which may explain the temporary deceleration in growth as they adapted to a predominantly pasture-based diet (Swatland, 1994).

The 8w calves achieved numerically higher ADG in the period from three to six months and so the difference in live-weight between the 8w and 12w calves reduced by 2 kg (from 6.7 kg to 4.7 kg) by six months of age. Compensatory growth is common in calves that have slow growth in early life (Brickell et al., 2009a; Curtis et al., 2018). As a consequence of this, there was no longer a significant effect of treatment on weight and girth at six months, there was however still a residual effect of weaning age on length and height. At six months the 12w calves were of larger frame size, this may be because of higher crude protein intake from additional MR consumed during the first 12 weeks of life (Shamay et al., 2005).

There was a significant interaction between treatment and length at three, six and nine months, respectively. At each of the aforementioned ages, the 12wH heifers had significantly greater values for length compared to all other treatment groups. However, this advantage had reduced by 12 months; indicating that the 8wL, 8wH and 12wL heifers experienced some compensatory growth in length over the winter period when a common diet was offered to all treatment groups. It appears that length is more likely to be static, compared to girth and height, thus signifying a different mechanism in the pattern of linear body growth when compared with live-weight (Moallem et al., 2010).

The H heifers had higher live-weight, ADG, length, girth, and height at nine months of age compared to the L heifers. This was attributable to the higher ADG they achieved from six to nine months (0.17 kg/day more than L heifers) due to the higher levels of concentrate supplementation (Pereira et al., 2017; Quintana et al., 2018). Feeding intensive diets during the rearing period is frequently used to increase heifer live-weight and thus reduce age at breeding and first calving (Le Cozler et al., 2019). A common diet was offered to the heifers during the winter and as a result there was no difference in ADG between L and H heifers from nine to 12 months, however carryover effects of post-weaning treatment on live-weight and linear body measurements were still evident at 12 months (Macdonald et al., 2005).

Low grass growth in early spring as a result of the growth pattern of perennial ryegrass (*Lolium perenne*; Hennessy et al., 2008), meant that the Y1 and Y2 heifers were offered a common diet of a forage crop for a period of six weeks before being reassigned to their post-weaning feed treatment groups and turned out to grass for their second grazing season. Although L heifers experienced some compensatory growth during this time (0.06 kg/day higher ADG relative to their H herd mates), H heifers still had significantly higher live-weight, girth, and height values at 15 months. This outcome was also reported in other studies whereby a carryover effect of live-weight and linear body measurements was observed long after the experiment had concluded (Little and Kay 1979; MacDonald et al., 2005).

Live-weight, ADG, and linear body measurements were significantly different for HF and JE at every time point during the experiment. This was expected due to the vast differences in live-weight and skeletal structure for mature HF and JE animals (Davis and Hathaway, 1956; Prendiville et al., 2011b).

Much of the previous research on heifer growth has been undertaken on heifers reared in confinement systems whereby feed of consistent quality is offered and so superior growth rates are possible (Van Amburgh et al., 2014). However, heifer feed source and quality is changeable in pasture-based production systems due to the nature of grass growth (O' Donovan et al., 2011). Nevertheless, as is evident from the present study, pasture-based heifers can achieve satisfactory growth rates from a predominantly pasture-based diet with some concentrate supplementation.

5.5.2 Fertility Performance

5.5.2.1 The Effect of Pre and Post-Weaning Treatment on Fertility

In the present study, 8w heifers were less likely to have initiated estrus activity prior to the commencement of the breeding season than 12w heifers. The 12wH heifers were at least 10 kg heavier at 14 months compared to the other treatment groups culminating in a numerical increase in the number of 12wH heifers that had attained puberty prior to MSD. Increased BW gain in early life has often been identified as the reason for a reduction in the pubertal age of the heifer (Macdonald et al., 2005; Archbold et al., 2012). Overall, fewer Y2 heifers had attained puberty prior to MSD than Y1 heifers; however, this may be due to differences in how pre-breeding estrus activity was monitored in Y2 heifers as a result of the global SARS-CoV-2 pandemic.

Post-weaning treatment and the interaction between pre and post-weaning treatment tended to be associated with the number of services required to attain pregnancy. A greater proportion of 12wH heifers (63%) needed just one service to achieve pregnancy compared to their 12wL (37%), 8wH (46%), and 8wL (48%) herd mates. The 12wH heifers were among the heaviest at MSD, indicating a positive relationship between BW and the number of services required for conception. Average daily gains of 0.81 kg/day have previously been associated with optimizing the number of services required to achieve a positive pregnancy result (Brickell et al., 2009b).

There was a significant interaction between weaning age and post-weaning feeding regime for days from MSD to conception. The interval from MSD to conception for 12wL and 12wH heifers in Y2 had increased by six and 10 days, respectively, compared to Y1. Year-on-year variation in fertility performance is typical in pasture-based dairy heifers (McNaughton et al., 2007). The 8wL heifers in Y2 had the shortest interval from MSD to conception and therefore tended (P= 0.051) to calve earlier. Earlier calving dates are favourable in a seasonal calving pasture-based system so that grazed grass, which is the cheapest source of nutrients, may be utilized as feed (Dillon et al., 1995) and so that the heifer will have more time to resume cyclicity prior to the commencement of the next breeding season (Lane et al., 2013).

There was a significant interaction between weaning age and post-weaning feeding regime for the 42-day pregnancy rate such that a greater proportion of the 8wL heifers became pregnant in the first six weeks of the breeding season compared to the 12wL heifers. This may be because of BW differences between the treatment groups in Y2 such that the 8wL heifers were on average 12 kg heavier at MSD than the 12wL heifers: the 12wL heifers accounted for approximately 44% of all Y2 heifers that were below target BW at MSD. The aforementioned difference in the 42-day pregnancy rate between 8wL and 12wL heifers in Y2 translated into a significant difference in the expected calving date. This is consistent with Archbold et al. (2012), who found that lighter heifers at MSD had later calving dates in the first lactation. Nevertheless, in the present study, 93 and 80% of Y1 and Y2 heifers, respectively, were pregnant within the first six weeks of the breeding season, which is in line with the national average six-week in-calf rate of 80% on Irish dairy farms (Shalloo et al., 2014).

There was no effect of weaning age on final pregnancy diagnosis, despite a greater proportion of 12w heifers having attained puberty prior to MSD. The heifers were on average 443 ± 12.7 days old at MSD and on average 461 ± 20.3 days old at conception; this suggests that fertility improves in line with the number of estrus cycles experienced by a heifer (Byerley et al., 1987; Wathes et al., 2014). The results suggest that within seasonal calving systems, weaning age does not impact the final pregnancy rate, which is similar to that reported by Morrison et al. (2009a) and Terre et al. (2009); this has positive ramifications for spring workload as weaning calves at eight-weeks can reduce the workload associated with calf rearing (Deming et al. 2018). However, pre-weaning nutrition has previously been found to account for up to 22% of the variation in first lactation milk production (Soberon et al., 2012a); therefore, the heifers in the present study should be monitored until the end of their first lactation to determine if early weaning influenced milk production.

In the present study, it was found that H heifers were less likely to achieve a positive pregnancy result compared to L heifers. This is consistent with previous research, such that heifers that were ahead of target BW observed a decline in reproductive efficiency (Ferrell, 1982; Archbold et al., 2012; Handcock et al., 2020). The 8wL heifers achieved perfect in-calf rates (100%) in both Y1 and Y2, and this is reflected in the superior pregnancy rates of the L treatment group. Overall, the Y1 and Y2 heifers had 8.6 and 6.5% empty rates, respectively, which were superior to the target empty rates of <10% in pasture-based systems (Donworth and Ramsbottom, 2018).

As is evident from the present study, BW and fertility are not mutually exclusive. Intensified feeding in the rearing period has been found to successfully increase BW and frame of dairy heifers (Pereira et al., 2017; Quintana et al., 2018), both of which are fundamental for early attainment of puberty (Little and Kay, 1979; Le Cozler et al., 2008; Lohakare et al., 2012). However, while growth may be easily accelerated by specific diet formulation in confinement systems of heifer rearing (Erickson and Kalscheur, 2020), manipulation of the diet is more difficult in pasture-based heifer rearing systems.

5.5.2.2 The Effect of Breed on Fertility

The effect of heifer breed on fertility performance has not previously been established (Macdonald et al., 2005); the present study, however, determined that HF had higher 42-

day pregnancy rates relative to JE. Nevertheless, there were discrepancies between the 42-day pregnancy rates of Y1 and Y2 HF (1.6 and 14.7%, respectively). Therefore, further investigation is required to determine which figure accurately represents the 42-day pregnancy rates for HF heifers. There was no breed effect on the other binary reproductive traits investigated. This agrees with previous research whereby no significant effect of breed on reproductive efficiency was found (Coffey et al., 2016; Prendiville et al., 2011a).

In a further attempt to determine if there were significant associations between breed, BW at MSD, and fertility performance, the HF and JE heifers in the current dataset were re-stratified by BW at MSD. It was found that HF heifers that weighed ≥ 336 kg at MSD (i.e., between 2 and 12% above target BW at MSD) tended to have older expected ages at first calving than their herd mates that were at and below target BW, respectively. Approximately 68% of the HF heifers weighed ≥ 336 kg at MSD were part of the 8wH and 12wH treatment groups, suggesting that a high feeding regime in the post-weaning period may have negative associations with AFC. The present study, however, only monitored the heifers until 15 months of age. Heavier heifers at breeding often have improved milk production performance in the first lactation (Macdonald et al., 2005; Handcock et al., 2019c), which has the potential to negate impaired reproductive efficiency. Although the increase in first lactation milk production may be advantageous, having heifers in excess of target BW can also be detrimental to subsequent calving intervals (Carson et al., 2002).

5.6 Conclusion

The post-weaning feeding regime had a greater influence on BW and LBM throughout the rearing period compared to weaning age. This may have positive implications for heifer rearing systems whereby meeting weight-for-age targets is vital for optimizing future production. However, there is a complicated relationship between BW and fertility performance, such that the heifers who were ahead of target at MSD observed a slight decline in reproductive efficiency in terms of pregnancy rates and expected AFC. This study suggests that the heifers that remained on the same plane of nutrition throughout the experimental period (i.e., 8wL and 12wH) generally excelled in terms of fertility performance. However, additional research is required to ascertain the overall effects of rearing strategy on milk production when heifers join the lactating herd.

Chapter 6: Short Communication: The Development of Equations to Predict Live-Weight from Linear Body Measurements of Pasture-Based Holstein-Friesian and Jersey Dairy Heifers

Livestock Science

DOI: 10.1016/j.livsci.2021.104693

6.1 Abstract

Monitoring the BW of dairy heifers and thus meeting weight-for-age targets is regarded as one of the most important aspects of a heifer rearing enterprise as it optimizes future production. This is particularly important in pasture-based heifer rearing systems, where growth is non-linear, due to seasonal variation in grass growth and quality. Data were collected throughout the rearing period to estimate the BW of pasture-based HF (n=130) and JE (n=57) dairy heifers using LBM. Body weight was regressed on HG, BV, and a polynomial of BL, HG, and WH; all equations were validated within-herd. All three equations were accurate predictors of BW for pasture-based dairy heifers ($R^2 > 0.92$ and RMSE < 19.1 kg); therefore, in the absence of weighing scales, BW can be successfully predicted using LBM. The equation, which utilizes the BV of the heifer, is proposed as the most suitable predictor of BW.

6.2 Introduction

Body weight has a greater effect on the attainment of puberty in pasture-based dairy heifers than that of age (Archbold et al., 2012). Therefore, achieving weight-for-age targets (Troccon, 1993) will ensure heifers have achieved puberty prior to breeding at 15 months, which is essential to maintain a compact calving pattern. Electronic scales are widely used to monitor animals' growth worldwide (Lukuyu et al., 2016). However, the uptake of technology among Irish and New Zealand farmers is particularly low (Teagasc, 2016b; McNaughton and Lopdell, 2012). In New Zealand, less than 5% of heifers had a BW recorded prior to calving (McNaughton and Lopdell 2012), while there were no figures in Ireland. Therefore, it is evident that the weighing of heifers is infrequent, and as such, farmers may be reluctant to invest in an electronic weighing scale.

In the absence of an electronic weighing scale, LBM such as HG, WH, and BL (Lukuyu et al., 2016) may be relatively accurate in their prediction of BW (Heinrichs et al., 1992) and are inexpensive to undertake. Previous research on the use of LBM to predict BW has been undertaken in confinement heifer rearing systems, where the growth trajectory is linear (Heinrich et al., 1992). However, in pasture-based systems, such as Ireland, grass growth and quality are highly variable (Hennessy et al., 2020), and consequently, heifer growth is non-linear (Handcock et al., 2019a). The relationship between LBM and BW varies with breed (Reis et al., 2008). Therefore, different prediction equations may be required for pasture-based heifers of contrasting breed groups, such as HF and JE (Handcock et al., 2019a). Therefore, the objective of the present study was to devise a series of equations to predict BW from LBM of different breed groups of pasture-based dairy heifers from birth to 15 months. This will be beneficial for pasture-based dairy farmers as it allows them to monitor the growth of heifers in the absence of a weighing scale. It was hypothesized that equations to predict BW of HF and JE heifers using different combinations of LBM would have a high prediction accuracy.

6.3 Materials and Methods

The present data were collected from heifers reared on the Dairygold Research Farm at Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Kilworth, Co. Cork, Ireland (52°09′N 8°16′W) between February 2018 and September 2020.

In brief, a 2 (weaning ages; 8w or 12w) x 2 (post-weaning planes of nutrition; H or L) factorial design was in place. There were 187 heifer calves born in 2018 (n=62 HF heifers and n=26 JE with mean bBW of 34.4 ± 4.67 kg and 23.0 ± 2.38 kg, respectively) and 2019 (n=68 HF and n=31 JE heifers with mean bBW of 35.2 ± 4.23 kg and 24.5 ± 2.88 kg, respectively) assigned to the study.

All calves received 3 litres colostrum within two hours of birth, followed by five feeds of transition milk. Calves were then grouped by age until they reached their respective weaning ages. When grouped, they were offered 6 L/ day of 26% CPMR, *ad-libitum* fresh, clean drinking water, concentrates, and straw.

Following weaning, calves were re-grouped according to their post-weaning treatment (H or L), and rotationally-grazed perennial ryegrass dominated swards until housing the following winter. During the first grazing season, the H heifers were offered 1.5 kg of concentrate/heifer/day; however, if grass quality and availability were poor, the quantity of concentrate offered increased to 2.5 kg concentrate/heifer/day. Similarly, the L heifers were offered 0.5 kg of concentrate/heifer/day; however, if grass quality and availability were poor, the concentrates offered were increased to 1.5 kg concentrate/heifer/day. A difference in concentrate offered was maintained between the H and L heifers at all times. Over-winter management was similar for treatments; from week one to three, and again during weeks nine to 15, heifers grazed *in-situ* forage brassica (Redstart), in addition to *ad-libitum* hay and 1 kg concentrates/heifer/day. During weeks four to eight of the over-winter period, heifers were housed and offered grass silage and 1.5-2 kg concentrate/heifer/day, depending on silage quality. At turnout to grass for their second grazing season, heifers were re-grouped by post-weaning treatment (H or L) and offered an all-grass diet. Contrasting pasture allowances were offered to create differences between the treatments; post-grazing heights of 4.5 and 3.5 cm were targeted for H and L heifers, respectively. The BW, ADG between weighing dates, and LBM throughout the experimental period are outlined in Table 6.1.

Body weight (kg; TruTest XR 3000, Tru-test Limited, Auckland, New Zealand) and LBM (cm) data were recorded twice a month from birth until nine months and every three months thereafter until breeding at 15 months. A soft measuring tape was used to measure the BL (horizontal distance from the top of the withers to the ischium) and HG (circumference of the animal's body measured directly behind the front legs). A specialized measuring stick (Nasco, Fort Atkinson, WI) was used to measure the WH (vertical distance from the ground to the top of the withers).

Table 6.1: Data available for regression analysis of Holstein-Friesian (HF) and Jersey (JE) heifers

	HF (n=130)		JE (n=57)	
	μ	SD	μ	SD
3 months				
Weight	87.3	11.47	68.1	10.60
ADG birth to 3 months	0.63	0.133	0.53	0.124
Length	75.9	4.78	71.1	6.199
Girth	108.0	5.94	99.0	7.892
Height	89.8	3.39	83.7	4.37
6 months				
Weight	148.9	18.57	113.5	13.25
ADG 3 to 6 months	0.73	0.165	0.55	0.145
Length	84.8	3.48	80.8	4.50
Girth	127.4	7.99	118.5	8.08
Height	100.4	4.22	93.3	3.08
9 months				
Weight	215.7	25.29	168.1	18.83
ADG 6 to 9 months	0.80	0.182	0.65	0.194
Length	97.4	3.44	92.9	3.39
Girth	145.4	6.76	136.2	5.89
Height	109.6	4.05	105.0	3.00
12 months				
Weight	253.9	28.50	200.0	18.63
ADG 9 to 12 months	0.45	0.135	0.38	0.150
Length	105.4	3.59	102.5	3.08
Girth	156.5	7.47	148.2	6.73
Height	115.9	4.43	109.9	3.31
15 months				
Weight	304.4	28.76	238.8	20.71
ADG 12 to 15 months	0.60	0.130	0.46	0.127
Length	110.0	3.45	107.5	3.19
Girth	166.2	6.41	157.0	5.76
Height	120.1	4.33	114.5	3.09

[1] ADG = average daily gain

6.3.1 Statistical Analysis

Statistical analyses were conducted using SAS (version 9.4; SAS Institute Inc., Cary, NC). Regressions of BW on LBM were tested (PROC REG) across the entire dataset and then for HF and JE separately. Stratifying the dataset by breed group was found to increase the accuracy of prediction, therefore verifying that separate comprehensive equations were required for pasture-based HF and JE heifers as growth was non-linear (Table 6.1 and Figure 6.1). Regressions of BW on HG, WH, BL, and their combinations were tested (PROC REG) prior to cross-validation, which aimed to validate a series of the best parameters. Three equations were selected for cross-validation such that equations that utilized one, two, and three LBM, respectively, were created. Within-herd validation involved stratifying the HF and JE datasets by birth year, pre and post-weaning treatment.

Numerical differences between the HF and JE datasets resulted in an average of 25 and 33%, respectively, of records from each stratum being removed for validation. The remaining records from each stratum were used to create the equations: heifers were not simultaneously present in the calibration and validation data sets. This process was repeated four and three times for HF and JE datasets, respectively, until all records had been tested using within-herd validation once. Regressions of BW on HG, WH, BL, and their polynomial combinations were then performed.

Body volume of the heifer was also regressed on BW, whereby BV was calculated using the formula to calculate cylinder volume:

$$Body\ volume = \pi r^2 h$$

where π = 3.14, r = (HG/2 π) and h = BL. Both linear and non-linear relationships were tested. All regression equations then underwent within-herd validation. The association between predicted and actual BW was assessed using regression analysis.

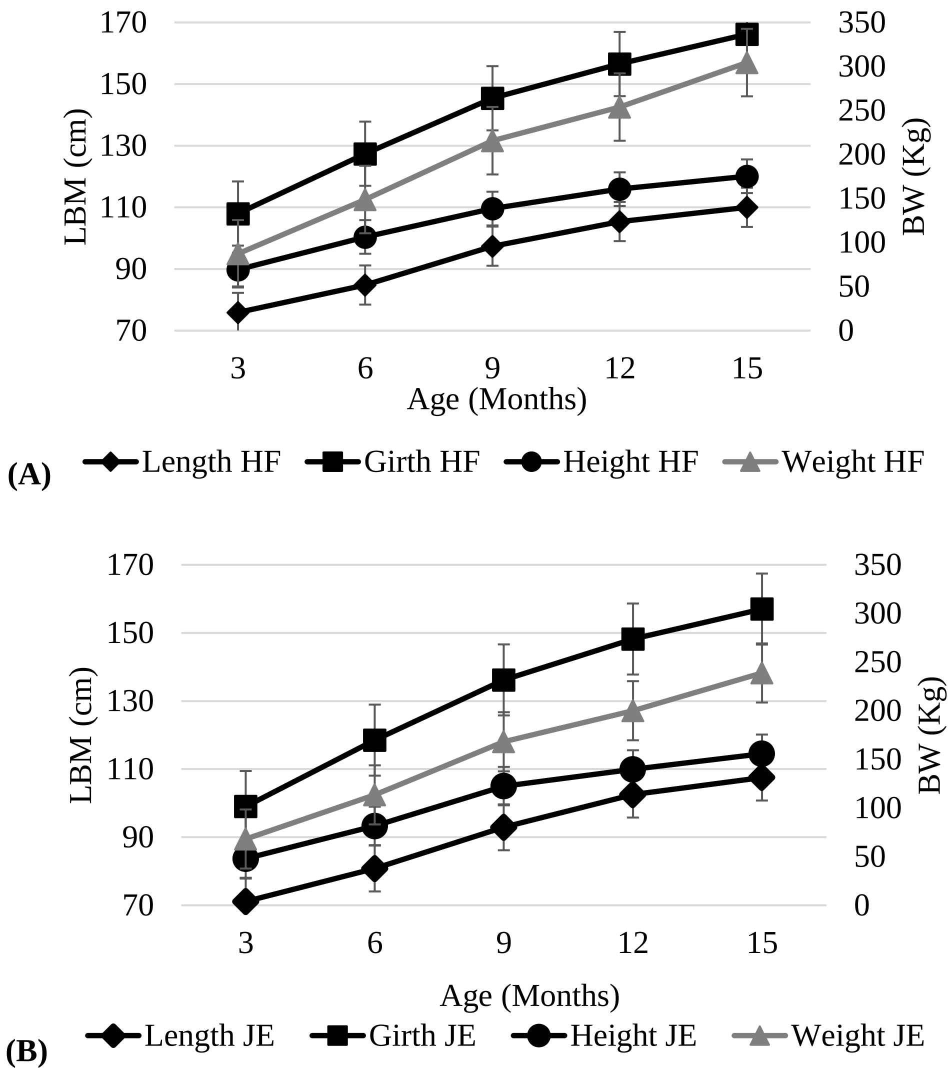


Figure 6.1: Body weight (BW; kg) and linear body measurements (LBM; i.e., length, girth and height; cm) of Holstein-Friesian (HF; A) and Jersey (JE; B) heifers.

The statistical methodology used to evaluate the accuracy of BW predicted by the model, compared with actual BW on 25 and 33% of the data for the HF and JE heifers, respectively, was similar to that of Ruelle et al. (2019). In brief, the R^2, RMSE, slope of the line, MSPE, RPE, and CCC were used to determine if the model accurately predicted BW. The MSPE is the sum of three components: mean bias $(M_m - P_m)^2$, line variation $S^2_p (1 - b)^2$ and random variation about the line, $S^2_m (1 - R^2)$, whereby each is expressed as a proportion of the total MSPE:

$$MSPE = \frac{\sum (M-P)^2}{n}$$

$$= (M_m - P_m)^2 + S_p^2 (1-b)^2 + S_m^2 (1-R^2)$$

where n is number of records, M and P are measured and predicted BW, respectively, Mm and Pm are mean values of M and P, respectively, S_m^2 and S_P^2 are variances of M and P, respectively, b is the slope of the line of P regressed on M; and R^2 is the coefficient of determination of the line. The RMSPE is the root of the MSPE. The RPE is calculated as:

$$\text{RPE} = \left(\frac{RMSPE}{M_m}\right) \times 100$$

The CCC is comprised of two components:

$$\text{CCC} = p \times Cb$$

where p is the Pearson correlation coefficient and Cb is the bias correction factor:

$$Cb = \frac{2 \times \sigma_m \times \sigma_p}{\sigma_m^2 + {\sigma^2}_p + \left(\mu_m - \mu_p\right)^2}$$

and σ_m, σ_p, μ_m and μ_P are the standard deviation and average of the measured and predicted data, respectively. The CCC evaluates the correlation between the actual and predicted BW and the deviation from the 45° line.

6.4 Results

The fitting statistics for the equations are outlined in Table 6.2, whereby values reported are the average of the four and three iterations for the HF and JE within-herd validations, respectively. All three equations accurately predicted BW (Figure 6.2) with RPE values of between 8.1 and 12.5%. In all equations, a high proportion of MSPE (>97.4%) was attributable to random variation. The equations to predict BW had average R^2 and RMSE values of 0.95 (range 0.92 – 0.97) and 14.8 kg (range 11.8 – 19.1 kg), respectively. Although still an excellent predictor of BW for HF and JE heifers (RPE 11.5 and 12.5, respectively), the equation that predicted BW using a single LBM, namely HG, resulted in inferior fitting statistics compared to the equation that utilized two and three LBM. Including all three LBM as a polynomial in the prediction equation improved RPE values by 3.4 and 3.6% for HF and JE heifers, respectively, compared to the equation that utilized one LBM. The equation that regressed BW on BV was also found to accurately predict BW, with RPE values of 9.0 and 10.3% for HF and JE heifers, respectively. The regression equations used to predict BW for HF and JE heifers are presented in Table 6.3.

Table 6.2: Comparison between the actual and predicted live-weight (kg) of Holstein-Friesian (A) and Jersey (B) heifers for different simulations using within herd validation

(A)

					Proportion of the MSPE					
	Measured	Predicted	Slope	RMSPE	Mean	Line	Random	RPE	CCC	C bias
Girth	166. 5	166.6	1.00	19.1	0.3	0.1	99.6	11.5	0.97	1.00
Body volume [1]	166. 5	166.6	1.00	15.0	0.1	0.6	99.4	9.0	0.98	1.00
Length, Girth, Height,Length^2, Girth^2 and Height^2	166.4	166.4	1.00	13.5	0.5	0.5	99.0	8.1	0.98	1.00

(B)

					Proportion of the MSPE					
	Measured	Predicted	Slope	RMSPE	Mean	Line	Random	RPE	CCC	C bias
Girth	130.6	130.6	1.00	16.3	0.6	0.4	99.0	12.5	0.96	1.00
Body volume[1]	130.6	130.6	1.00	13.5	1.8	0.8	97.4	10.3	0.97	1.00
Length, Girth, Height,Length^2, Girth^2 and Height^2	130.6	130.5	1.00	11.7	0.2	0.1	99.8	8.9	0.98	1.00

[1] Body volume was regressed on live-weight whereby the formula to calculate cylinder volume was utilized

[2] RMSPE = root mean square prediction error; MSPE = mean square prediction error; RPE = relative predicted error; CCC = concordance correlation coefficient; Cbias = bias of the concordance correlation coefficient

Table 6.3: Regression equations created using the lengths (BL), girths (HG), heights (WH) and body volumes (BV) of Holstein-Friesian (HF; A) and Jersey (JE; B) heifers, respectively

(A)

	Equation	R^2	RMSE
Girth	-235.2 + 3.2 (HG)	0.93	19.13
Body volume	8.3 + 0.0012 (BV)	0.96	15.06
Length, Girth, Height, Length², Girth² and Height²	-89.2 - 3.3 (BL) -1.2 (HG) + 4.3 (WH) + 0.027 (BL^2) + 0.010 (HG^2) + 0.009 (WH^2)	0.97	13.23

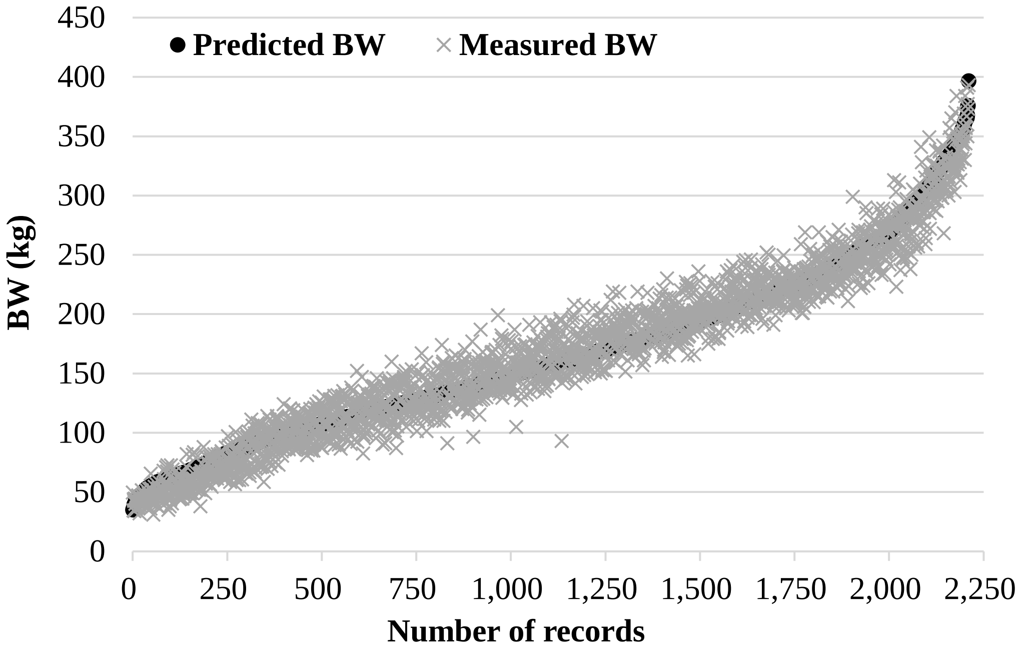
(B)

	Equation	R^2	RMSE
Girth	-198.6 + 2.7 (HG)	0.92	16.31
Body volume	7.1 + 0.0011 (BV)	0.95	13.37
Length, Girth, Height, Length², Girth² and Height²	-7.5 - 3.4 (BL) + 0.1 (HG) + 1.4 (WH) + 0.0028 (BL^2) + 0.004 (HG^2) + 0.003 (WH^2)	0.96	11.79

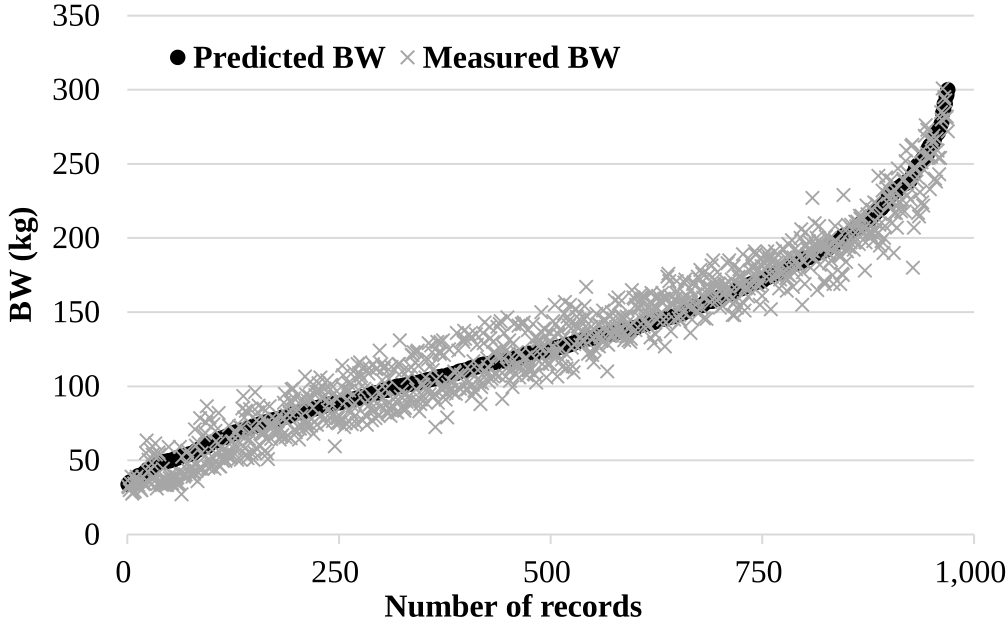
[1] RMSE = root mean square error

6.5 Discussion

The aim of the present study was to develop equations to predict the BW of growing dairy heifers in a pasture-based system. Equations have been developed previously (Heinrichs et al., 1992); however, these animals were reared in confinement heifer rearing systems where precision nutrition ensures greater efficiency of nutrient utilization (Zanton and Heinrichs, 2008b). Heifers in pasture-based heifer rearing systems, such as that in Ireland, are offered a predominately grazed-grass diet, with concentrate supplementation when grass growth and quality are poor. Consequently, heifers reared in pasture-based systems follow a seasonal growth pattern (Handcock et al., 2021). Similar to Heinrichs et al. (1992), HG was highly correlated ($R^2 > 0.92$ and RPE 11.5 and 12.5% for HF and JE, respectively) with BW and was therefore used to develop a simple equation for the prediction of BW. Using a single LBM to predict BW may be useful for farmers who wish to monitor the growth of their heifers but may not have time to measure several dimensions of skeletal growth. The inclusion of two or more LBM in the regression equation slightly improved BW prediction: the regression equation for BV utilized HG and BL and was found to predict HF and JE heifer BW to within 13.4 and 15.1 kg, respectively. Body volume was previously found to be highly correlated with BW of native Indonesian cows (Paputungan et al., 2015); however, to the best of the author's knowledge, BV has never been used to predict BW of pasture-based heifers. Similar to Reis et al. (2008), including three independent LBM in the equation increased prediction accuracy. Furthermore, polynomial regression of BL, HG, and WH on BW improved the fit statistics further, with an R^2 of 0.97 and 0.96 and RMSE of 13.2 and 11.8 kg for HF and JE heifers, respectively. However, the polynomial regression equation was only marginally better than the BV equation; therefore, from a practical perspective, the BV equation is more appropriate for a labour-intensive dairy farm.



(A)



(B)

Figure 6.2: Comparison between the measured body weight (BW; x) and predicted body weight (●) of Holstein-Friesian (A) and Jersey (B) heifers.

6.6 Conclusion

The equations developed in this study are all highly effective in predicting the BW of pasture-based HF and JE dairy heifers. The equation, which utilizes the BV of the heifer, is proposed as the most suitable predictor of BW. Despite utilizing just two LBM, the equation based on BV displays a high prediction accuracy and will enable dairy farmers to monitor the growth of their heifers in the absence of a weighing scale.

Chapter 7: The Associations Between Age and Body Weight at First Calving in Spring-Calving Holstein-Friesian Dairy Cows with Productive Performance

7.1 Abstract

Age at first calving is one of the most important determinants of heifer rearing costs; a younger AFC is recommended in order to minimize the non-productive period. A younger AFC has previously been associated with a reduction in milk production. Increasing the BW at first calving may negate the suboptimal performance associated with a younger AFC. The objective of this study was to quantify the associations, using data collected on Irish research farms over a 15-year period, between age and BW at first calving with performance thereafter in pasture-based seasonal-calving HF dairy heifers. After edits, the calving performance, milk production, reproduction, and BW and BCS data from 1,323 heifers across 2,924 parity one to three calving events were available for analysis. While a younger AFC was not associated with a reduction in milk yield, it was associated with reduced milk fat and protein percentages. A heavier BW at first calving, at the same AFC, benefited milk yield and milk fat percentage throughout the first three lactations. Although the youngest, lightest heifers were more likely to experience dystocia at first calving, they were not susceptible to dystocia in subsequent parities. A heavier BW at first calving was also consistent with a reduction in the number of services required to conceive. Heavier heifers at first calving were also heavier and more conditioned throughout the first and second lactation. Although future performance was optimized when heifers had a median age (between 738 and 768 days of age) and BW at first calving (between 516 and 550 kg), the optimum combination of age and BW at first calving is a function of milk price and costs of production. Furthermore, these findings are confined to the limits of age and BW at first calving in the present study.

7.2 Introduction

Age at first calving is of particular importance in spring-calving pasture-based production systems, such as that in Ireland and New Zealand, where cows typically calve within a short period in order to maximize the utilization of grazed grass as a feed source (Dillon et al., 1995). An AFC of between 22 and 26 months of age will ensure that a compact seasonal calving pattern is maintained (Evans et al., 2006; ICBF, 2019), because heifers that calve later are less likely to be successfully bred early in consecutive years (Hayes et al., 2019). This practice increases not only the unproductive lifespan of the heifer but also heifer rearing costs (Gabler et al., 2000; Moran and Chamberlain, 2017). Heifer rearing is a substantial cost to the dairy farmer; it costs on average €1,545 to rear a heifer from birth until calving at 24 months (Shalloo et al., 2014), representing 15-20% of total production costs on a dairy farm (Heinrichs, 1993). It has been estimated that this cost is not repaid until the heifer completes 1.63 lactations, although this is a function of milk price and input costs (Berry et al., 2015). A reduction in AFC from 25 to 24 months of age has the potential to reduce the cost of rearing by up to 4.3% (Tozer and Heinrichs, 2001).

The AFC of US dairy heifers has declined in recent years, with consequences for production potential (Hare et al., 2006). A one-month reduction in AFC (from 24 months of age to 23 months of age) is associated with a reduction in milk production (Berry and Cromie 2009; Heinrichs and Heinrichs, 2011; Mohd Nor et al., 2013), although this reduction appears to be confined to the first lactation (Wathes et al., 2014; Eastham et al., 2018; Sawa et al., 2019). Age at first calving has also been associated with survivability; heifers that calved for the first time between 22 and 26 months of age were more likely to survive to subsequent lactations than their herd mates that were older than 26 months at first calving (Evans et al., 2006; Sherwin et al., 2016).

From a study of Australian HF heifers, Dobos et al. (2001a) demonstrated how a heavier BW at first calving could compensate for the impact of a younger AFC on lactation yield. Many studies have reported a linear relationship between BW at first calving and milk production until the second (McNaughton and Lopadell, 2013) and third lactations (Dobos et al., 2001b), while Handcock et al. (2018) observed a curvilinear relationship between BW at 21 months of age and milk production in the first lactation. Non-linear relationships between BW at calving and subsequent reproductive performance have been reported in dairy cows (Roche et al., 2007c) with compromised reproduction in very heavy heifers (Carson et al., 2002; McNaughton and Lopadell, 2013). A greater mobilization of body reserves in early lactation may delay the resumption of ovarian function (Butler and Smith, 1989), and as a result, the calving to conception interval is increased (Shrestha et al., 2004).

Previous studies have focused on the associations between either AFC (Berry and Cromie, 2009) or BW at first calving of dairy heifers (Handcock et al., 2018) and subsequent production and reproduction but, because AFC and BW at first calving are not independent, these should be considered together, as was undertaken by Dobos et al. (2001a; 2001b). The objective of the present study, therefore, was to quantify the independent associations between age and BW at first calving in spring-calving HF dairy heifers with a series of performance metrics. The performance metrics considered were calving, fertility, BW, BCS, and milk production. The results from this study will assist the dairy industry in determining the ideal combination of target AFC and live weight at first calving so that subsequent production performance is optimized. It was hypothesized that heifers that were older and heavier at first calving would have improved production thereafter.

7.3 Materials and Methods

The data used in the present study originated from HF females that partook in several experimental studies (Dillon et al., 2006; Ganche et al., 2013; Horan et al., 2006; Humphreys et al., 2009; Kennedy et al., 2006, 2009, 2011; McCarthy et al., 2007, 2015; McEvoy et al., 2008; O' Sullivan et al., 2019; Patton et al., 2016; Prendiville et al., 2009; Reid et al., 2015; Walsh et al., 2008; Wims et al., 2013) between the years 2003 and 2017 inclusive. The studies either compared alternative genotypes of HF dairy cows on various grassland production systems or focused on the development of optimized pasture-based production systems. Experiments were carried out on eight Teagasc research farms located around the country of Ireland. Rotational grazing systems were in place on all farms targeting a 300-day grazing season. On average 500 kg concentrates/cow/year were fed, although it varied from 250-1100 kg concentrates/cow/year depending on the experimental treatments applied.

7.3.1 Heifer Management

All heifers were reared in accordance with Teagasc guidelines (Barry, 2020). In brief, high quality colostrum (>50 mg/ml IgG; Godden, 2008) was fed to all calves within an hour of birth. Heifers were then fed 4-5 litres/calf/day of transition milk (i.e., the milk collected from the second to the sixth milking post-calving of recently calved cows) for four days before MR was offered (26% CP; Volac, Church Street, Killeshandra, Co. Cavan, Ireland) at a rate of 6 litres/calf/day and mixed at a reconstitution rate of 15%. Heifers were grouped from five days of age and were offered fresh water, ad-libitum concentrates and straw or hay in their respective group pens, where they remained until gradual weaning at approximately 15% of mature BW (generally 8-12 weeks old).

Post-weaning, a pasture-based diet (Target pre-grazing yield of 1,400-1,600 kg DM/ha > 4 cm) supplemented with of 1–2 kg of concentrate was fed. During their first winter, heifers were offered ad-libitum grass silage and a daily concentrate allocation of 1-2 kg concentrate when they were housed from approximately mid-November. Weather permitting, heifers were turned out to pasture the following February and offered an all-pasture diet. The breeding season started mid-April, when heifers were approximately 15 months old, and lasted 12 weeks.

Heifers were dosed with an anthelminthic every 6-8 weeks during their first season at grass to control for lungworm and stomach worm. In the second season at grass, dosing occurred at turnout and any coughing animals were dosed as required thereafter. Coccidiosis was controlled by administering diclazuril (Vecoxan®, Elnco Animal Health, Basingstoke, UK). Heifers were managed in accordance with the 'Moorepark blueprint', a model which proposes methods of best farming practice in domain areas such as grass, supplementation, labour, housing, lactation length, replacement rate, cull cows and calf value (Crosse et al., 2000). If weather conditions were poor post-calving, on/off grazing (grazing for 2-4 hours after milking with silage or concentrate supplementation) was practiced until weather conditions permitted full-time grazing (Kennedy et al., 2009). During the main grazing season, grass provided sufficient nutrients for milk production; as grass quality deteriorated in the autumn, concentrate supplementation was required to maintain milk production. Cows were dried off 8-12 weeks prior to calving to optimize milk production in the subsequent lactation. Cows were fed ad-libitum grass silage in order to ensure a BCS of 3.25 at calving; BCS was assessed on a scale of one to five (Edmonson et al., 1989) where one represented emaciation and five represented obesity.

7.3.2 Animal Measures

Heifers were weighed on average nine times from birth until first housing and monthly thereafter (TruTest XR 3000, Tru-test Limited, Auckland, New Zealand). Post-calving, BW was recorded approximately once weekly on exit from the milking parlour after morning milking. The farm manager on each respective farm measured BCS 1-2 times per month. Milk yield was recorded daily using electronic milk meters (Dairymaster, Causeway, Co. Kerry, Ireland). Milk samples, collected once weekly from successive morning and evening milking, were analysed using the Dairyspec infrared manual FT model (Make-Bentley systems, Chaska, MN, USA) to determine milk fat, protein, and lactose concentration.

7.3.3 Data Editing

Calf birth BW, calving difficulty, milk yield, milk composition, fertility, BW, and BCS data were obtained from the research herds over a 15-year period between 2003 and 2017, inclusive. The estimated breeding value of each animal for carcass weight (a proxy for animal BW) was obtained from ICBF national genetic evaluation in 2018.

Data were available on 7,183 lactations from 2,665 spring-calving HF animals. Only data from the first three consecutive lactations, where available, were retained, although every animal had to have a first parity record; 4,411 lactations from 2,018 animals remained. Age at first calving was defined as the age, in days, when the animal calved for the first time. Only animals with an AFC between 20 and 28 months old were retained; 4,298 lactations from 1,963 animals remained. For further consideration in the analysis, only heifers with a BW measured between five and 20 days after first calving were retained. After all edits, 2,924 lactations from 1,323 animals remained for analysis.

The 1,323 heifers were stratified into four groups based on their AFC. The thresholds delineating the different AFC strata were ≤723 days, between 724 and 737 days, between 738 and 768 days, and ≥769 days. Prior to the stratification on BW at first calving, the actual BW was adjusted for both differences in genetic merit for carcass weight obtained from the national genetic evaluations as well as the day post-calving when the first BW was taken. To achieve this, a multiple linear regression was fitted whereby BW recorded post-calving was regressed on both days in milk at weighing and estimated breeding value for carcass weight. The resulting residuals from the model, once summed with the model intercept, were stratified into four groups, with an equal number of heifers in each stratum. The threshold BW values delineating the different strata were ≤493kg, between 494 kg and 515 kg, between 516 kg and 550 kg, and ≥551 kg.

7.3.3.1 Calving Performance

A total of 2,924 parity one to three calving events from all 1,323 animals were available for the analysis of calving performance variables. Calving difficulty was recorded by farm employees as 1) normal calving, 2) some assistance, 3) considerable difficulty, or 4) veterinary assistance. Only 2,860 records from 1,317 animals for which a calving difficulty score had been recorded were retained. For the purpose of the present study, two new variables were defined: assistance and dystocia. Assistance was assigned either zero (no assistance) or one (some assistance required, including considerable difficulty or veterinary assistance). Dystocia was assigned either zero (normal calving or just some assistance required) or one (considerable difficulty or veterinary assistance required).

Information was available on calf birth BW, whether the birth was a singleton or multiple, and whether or not the calf suffered from perinatal mortality. For the purpose of the present study, perinatal mortality was defined as the death of a calf either during parturition or up to 72 hours after birth; animals that gave birth to a calf that was born dead or died within 72 hours of birth were assigned a value of one, otherwise animals were assigned a value of zero. Only cows that gave birth to calves that weighed between 23 kg and 58 kg at birth, which were deemed acceptable birth BW for HF calves, were retained for analysis (2,520 parity one to three calving events from 1,203 animals were available for analysis of calving performance variables). A contemporary group for the analysis of calving performance traits, which was defined as herd-year-season, was developed using an algorithm used for most of the genetic evaluations in Ireland (Berry et al., 2013). Animals, within parity and herd, which had calved within 10 days of each other, were grouped together. If the number of animals in a contemporary group was less than 10, then the contemporary group was merged with the adjacent group as long as there were no more than 30 days between the start date of one group and the end date of the adjacent group. Only contemporary groups with at least five animals were retained; 1,921 parity one to three calving events from all 1,048 animals were available for analysis of calving performance variables.

7.3.3.2 Milk Production

A total of 126,410 milk test-day records from 1,323 cows across 2,924 lactations were available for analysis. Only data from lactations where each cow had at least 30 milk test-day records, with at least one milk record within the first 10 days of lactation and at least one milk record >230 days post-calving, were retained for analysis (124,195 milk test day records from 1,323 animals across 2845 lactations remained). The Wilmink exponential function (Wilmink, 1987), was used to predict different phenotypes of milk yield. The Wilmink function was described as

$$y_t = a + be^{(-0.05t)} + ct,$$

where y_t represents milk yield (kg) on day t of lactation, whereas a, b and c are related to the increase in production towards peak yield, the height of the curve where -0.05 signifies the time of peak lactation, and the subsequent decline after peak milk yield has been achieved, respectively. The regression parameters were estimated for each cow lactation separately using PROC NLIN (SAS, 2006). The first derivate of the Wilmink function with respect to time (dMilk/dt) was solved for each cow lactation and used to determine days in milk at peak milk yield. Abnormal fitting milk yield curves were omitted from the analysis (2,658 lactations remained). The Wilmink exponential function (Wilmink, 1987) was not an accurate predictor of milk constituents; milk constituents were instead determined using the mean values for fat, protein and lactose percent in the first 60 and 305 days of lactation, respectively. Somatic cell count was normalized to SCS by taking the natural logarithm of SCC/1,000 in animals. Only data from lactations where each cow had at least four SCS records, with at least one milk record within the first 60 days of lactation, were retained (2,562 lactations from 1258 animals). SCS in the first 60 and 305 days were calculated using the mean of all test day records in the first 60 days and 305 days of lactation, respectively. A contemporary group for the analysis of milk production, which was defined as experimental treatment-year-season, was developed using an algorithm used for most of the genetic evaluations in Ireland (Berry et al., 2013). Animals, within parity and treatment, which had calved within 10 days of each other, were grouped together. If the number of animals in a contemporary group was less than 10, the contemporary group was merged with the adjacent group as long as there were no more than 30 days between the start date of one group and the end date of the adjacent group. Only contemporary groups with at least five animals were retained; 2,066 lactations from 1,171 animals were available for analysis of the milk production traits.

7.3.3.3 Fertility

A total of 2,924 fertility records from 1,323 animals were available for the analysis of fertility performance variables such as CFS, number of services and calving interval. Calving to first service interval was defined as the number of days from the date of calving to the first recorded service; only animals that had a CFS of between 10 and 250 days were retained (2,842 fertility records from 1,300 animals remained). Number of services was defined as the number of services (AI or natural) required to achieve pregnancy. Calving interval was defined as the number of days between consecutive calvings, only animals that had a calving interval of between 300 and 800 days were retained; 2,839 lactation records from 1,299 cows remained. A contemporary group for the analysis of fertility performance traits, which was defined as experimental treatment-year-season, was developed using an algorithm used for most of the genetic evaluations in Ireland (Berry et al., 2013). Animals, within parity and treatment, which had calved within 10 days of each other, were grouped together. If the number of animals in a contemporary group was less than 10, then the contemporary group was merged with the adjacent group as long as there were no more than 30 days between the start date of one group and the end date of the adjacent group. Only contemporary groups with at least five animals were retained; 2,332 fertility records from 1,228 animals were available for analysis of fertility performance traits.

7.3.3.4 Body Weight and Body Condition Score

A total of 103,659 BW and 50,317 BCS records from 1,323 animals across 2,924 lactations were available. Animals were required to have a BW and BCS record between five and 20 days post-calving for parities one, two and three, respectively, for that parity to be considered in the analysis of BW and BCS performance variables; 66,221 BW and 41,027 BCS records from 1,175 animals across 2,033 lactations were available. Mean BW and BCS in the first 60 and 305 days of lactation, respectively, was defined as the mean BW and BCS of each cow in the first 60- and 305-days post calving, respectively. Nadir BW and BCS was defined as the first appearance of the lowest BW and BCS record, respectively, in the first 105 days of a lactation. Days to nadir was defined as the time, in days, between calving and the date of nadir; 1,585 lactations from 1,019 animals were available for further analysis. Body weight and BCS change from calving to nadir was calculated as the BW or BCS at calving, minus the BW or BCS at nadir. A contemporary group for the analysis of BW and BCS traits, which was defined as experimental treatment-year-season, was developed using an algorithm used for most of the genetic evaluations in Ireland (Berry et al., 2013). Animals, within parity and treatment, which had calved within 10 days of each other, were grouped together. If the number of animals in a contemporary group was less than 10, the contemporary group was merged with the adjacent group as long as there were no more than 30 days between the start date of one group and the end date of the adjacent group. Only contemporary groups with at least five animals were retained; 1,149 BW and BCS records from 835 animals were available for analysis of BW and BCS performance traits.

7.3.4 Analysis

All analyses were undertaken using either linear mixed models (where the dependent variable was a continuous trait) or generalized linear mixed models (where the dependent variable was a binary trait). In all models, cow was included as a repeated effect with the most parsimonious covariance structure assumed among records within cow.

In the analysis of calving performance variables, contemporary group was included in the model as a random term. Fixed effects considered in the model for the analysis of the calving performance variables were sex of the calf, parity, AFC stratum, BW at first calving stratum, a two-way interaction between AFC and BW at first calving stratum, and a three-way interaction between AFC, BW at first calving stratum and parity. Only interaction terms which improved ($P<0.05$) the fit to the data were retained.

In the analysis of post-calving traits (i.e. milk production, fertility performance and BW and BCS performance), contemporary group was included in the model as a random term. Fixed effects considered in the linear mixed model for the analyses of these variables were parity, farm , AFC stratum, BW at first calving stratum, a two-way interaction between AFC and BW at first calving stratum, and a three-way interaction between AFC, BW at first calving stratum and parity. Only interaction terms which improved ($P<0.05$) the fit to the data were retained.

7.4 Results

The mean (standard deviation in parentheses) AFC of the dataset was 731 (28.1) days. The mean (standard deviation in parentheses) BW at first calving of the dataset was 469 (47.7) kg.

7.4.1 Calving Performance

The mean (standard deviation in parenthesis) birth weight of the calves was 37.2 kg (6.12 kg). Neither AFC, BW at first calving, nor the interaction between AFC and BW at first calving, were associated with birth BW of the calf, the incidence of multiple births, or the death of a calf up to 72 hours post-birth. Age at first calving was not associated with the incidence of dystocia, but BW at first calving was associated with the incidence of dystocia (P=0.005), such that cows that weighed ≤493 kg at first calving had a 2.40 times (95% confidence interval: 1.41 to 4.08) greater odds of experiencing dystocia compared to those that weighed ≥551 kg at first calving (Table 7.3). The interaction between BW at first calving and parity was not associated with the incidence of dystocia. Although AFC was not associated with whether or not assistance was required during calving, BW at first calving tended to be associated with the requirement for assistance during calving (P=0.083). The cows that weighed between 494 and 515 kg at first calving had a numerically lower odds of an assisted calving compared to the other BW at first calving strata (Table 7.3).

7.4.2 Milk Production

Mean performance for milk production variables are summarized in Table 7.1. Body weight at first calving was associated with milk yield (P<0.001; Figure 7.1) in the first 60 and 305 days of lactation. The biggest increase was observed when BW at first calving increased from between 494 and 515 kg to between 516 and 550 kg; the 60- and 305-day milk yields increased by 43.3 and 176.3 kg, respectively. The interaction between BW at first calving and parity was associated with 60- and 305-day milk yields (P≤0.034). Body weight at first calving was also associated with peak milk yield, and the length of time (in days) from calving until peak milk yield (P<0.001; Figure 7.2). Cows that were ≥551 kg at calving had the highest peak milk yields, and reached peak milk yield on average 2.8 days before cows that weighed ≤493 kg at first calving. Cows with heavier BW at first calving also had higher peak milk yields in subsequent lactations (P= 0.029).

Table 7.1: Mean and standard deviation (SD) values of milk production traits across 2,066 parities.

Trait	Mean	SD
60-day milk yield (kg)	1337	260.2
305-day milk yield (kg)	5439	948.3
peak milk yield (kg)	24.3	4.44
60-day fat percent (%)	4.6	0.53
305-day fat percent (%)	4.4	0.46
60-day protein percent (%)	3.4	0.19
305-day protein percent (%)	3.6	0.21
60-day SCS (units)	3.8	1.05

[1] SCS= Somatic Cell Score

The 3-way interaction between AFC, BW at first calving and parity was associated with mean 60-day milk protein percent (P=0.008; Figure 7.3). Age at first calving was associated with mean 305-day protein percent (P=0.039), such that the cows aged 724-737 days and 738-768 days at first calving had a higher mean 305-day milk protein percentage (3.63%) than the cows aged ≤723 days and ≥769 days at first calving (3.60%). The interaction between AFC and parity was not associated with 305-day milk protein percentage.

Body weight at first calving was associated with mean milk fat percentage in the first 60 (P<0.001) and 305 (P=0.004) days of lactation (Figure 7.4). The interaction between BW at first calving and parity was associated with 60- (P= 0.005) and 305-day milk fat percentage (P=0.006). Age at first calving was also associated with mean milk fat percentage in the first 60 (P=0.010) and 305 days of lactation (P=0.009), such that there was an increase of 0.11% in 60- and 305-day mean milk fat percentage, respectively, as AFC increased from ≤723 to between 738-768 days. Nevertheless, the cows in the oldest AFC strata (≥768 days of age), experienced a 0.04 and 0.08%, reduction in mean 60- and 305-day milk fat percentage, respectively. The interaction between AFC and parity was neither associated with 60- nor 305-day milk fat percentage. Neither AFC nor BW at first calving were associated with mean 60- and 305-day milk lactose percentage, and mean 60- and 305-day SCS, respectively.

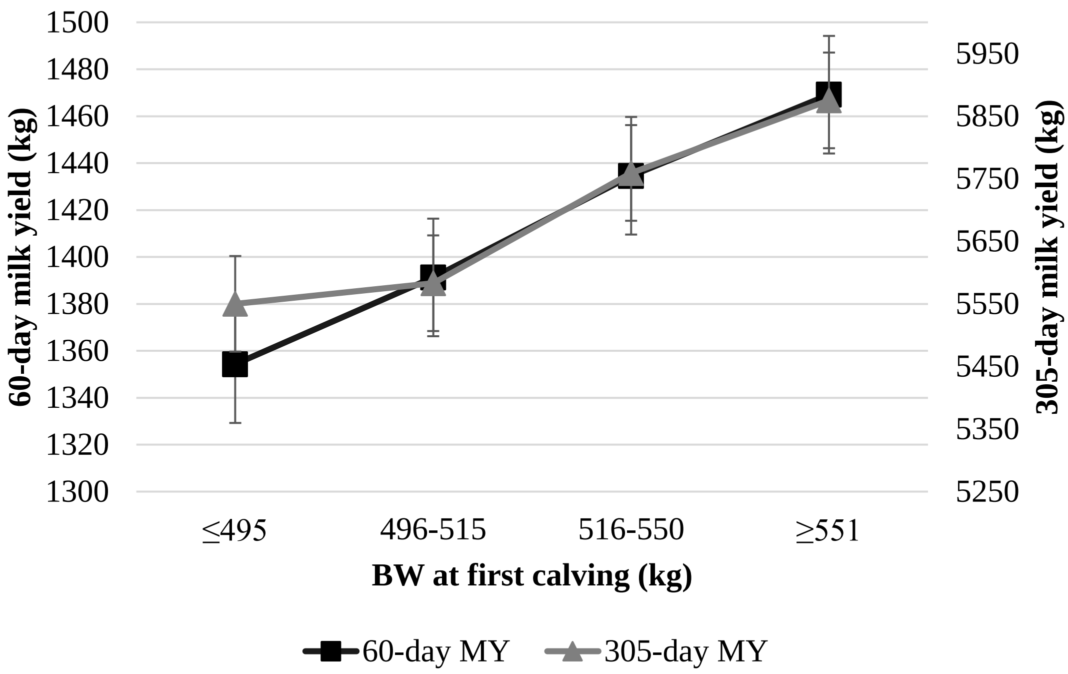


Figure 7.1: Least squares means, estimated using a linear mixed model, showing the association between body weight (BW) at first calving and 60-day (squares) and 305-day milk yield (triangles).

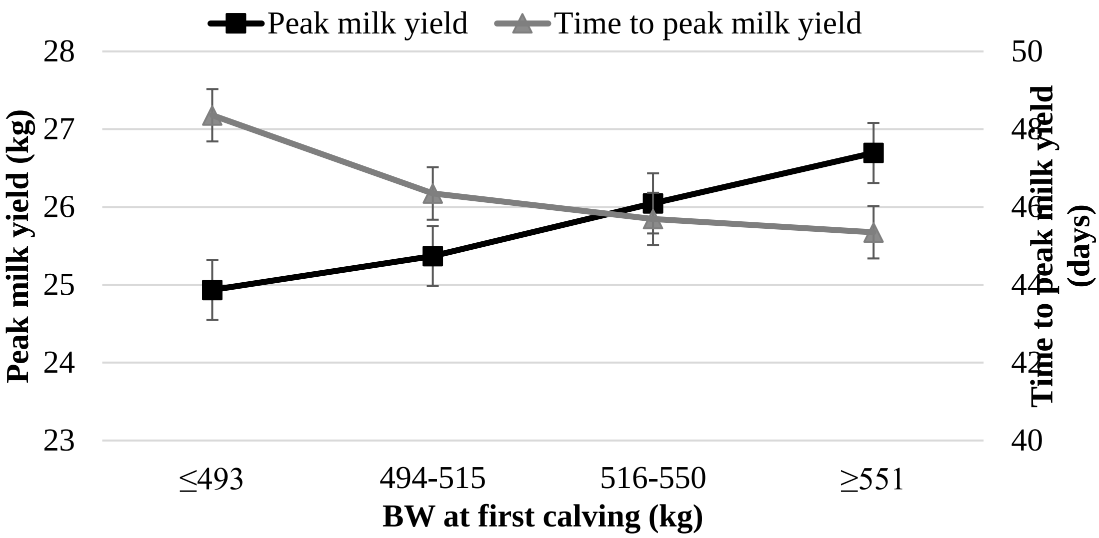
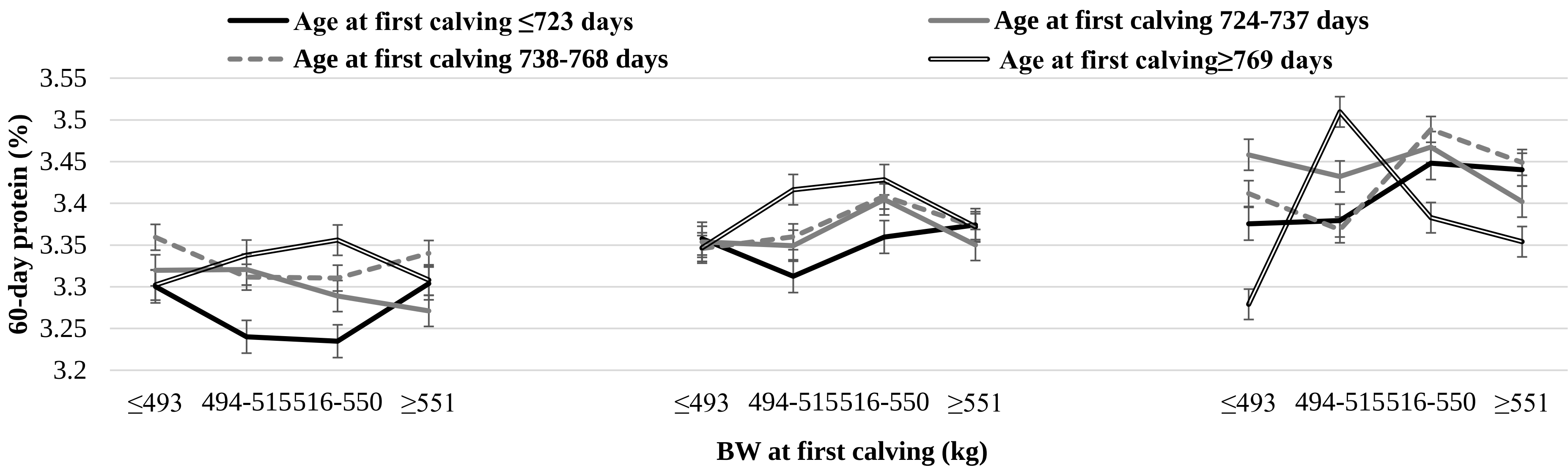


Figure 7.2: Least squares means, estimated using a linear mixed model, showing the association between body weight (BW) at first calving and peak milk yield (squares) and time to peak milk yield (triangles), respectively.

7.4.3 Fertility Performance

Age at first calving was associated with CFS (P<0.001) such that animals in the oldest AFC stratum (≥769 days) were served 11.7 days earlier than the animals in the youngest AFC stratum (≤723 days). The interaction between AFC and parity was associated with CFS (P<0.001). Body weight at first calving tended to be associated with CFS (P=0.080); the cows in the lightest BW at first calving strata (≤493 kg) had reduction (2.6 days) in CFS compared to the cows in the heaviest BW at first calving strata (≥551 kg). Body weight at first calving was associated with the number of services required to achieve pregnancy (P=0.010). The animals that weighed ≤493 kg and 494-515 kg at first calving required 1.85 and 1.86 services to achieve pregnancy, respectively. In contrast, the animals that weighed 516-550 kg and ≥551 kg at first calving required 1.67 and 1.68 services to achieve pregnancy, respectively. The interaction between BW at first calving and parity was not associated with the number of services required to achieve pregnancy. Neither AFC nor BW at first calving were associated with calving interval (days).



3688

3689 **Figure 7.3:** The interaction between age at first calving (days), body weight (BW) at first calving (kg), and parity for mean protein percentage
3690 in the first 60 days of lactation.

Body weight at first calving was associated with the number of services required to achieve pregnancy (P=0.010). The animals that weighed ≤493 kg and 494-515 kg at first calving required 1.85 and 1.86 services to achieve pregnancy, respectively. In contrast, the animals that weighed 516-550 kg and ≥551 kg at first calving required 1.67 and 1.68 services to achieve pregnancy, respectively. The interaction between BW at first calving and parity was not associated with the number of services required to achieve pregnancy. Neither AFC nor BW at first calving were associated with calving interval (days).

Table 7.2: Mean and standard deviation (SD) values of Body Weight (BW) and BCS performance traits across 1,149 parities.

Trait	Mean	SD
60-day BW (kg)	475	53.8
305-day BW (kg)	495	53.9
60-day BCS (units)	3.1	0.26
305-day BCS (units)	2.9	0.20
Nadir BW (kg)	451	52.0
Nadir BCS (units)	2.8	0.24
Weight loss to nadir (kg)	44	27.0
Time to nadir BW (days)	52	26.3
BCS loss to nadir (units)	0	0.28
Time to nadir BCS (days)	56	26.9

[1] BCS= Body Condition Score

7.4.4 Weights and Body Condition Score

Mean performance for the BW and BCS traits analysed are summarized in Table 7.2. Neither AFC, nor the interaction between AFC and BW at first calving were associated with any of the BW and BCS traits. With the exception of time (in days) taken to reach nadir BW and BCS, BW at first calving was associated with all of the BW and BCS performance traits (Table 7.4).

Table 7.3: Association between Body Weight (BW) at first calving (kg) and the incidence of assistance and dystocia.

Variable	BW at first calving	OR	95% CI	Pr > F
Dystocia	≤493	1		0.005
	494-515	0.6	0.39-0.98	
	516-550	0.53	0.33-0.86	
	≥551	0.42	0.25-0.71	
Assistance	≤493	1		0.083
	494-515	0.77	0.60-0.98	
	516-550	1.02	0.80-1.30	
	≥551	0.94	0.73-1.20	

In general, as BW at first calving increased, so too did mean 60- and 305-day BW, and BCS, respectively. Similarly, as BW at first calving increased, so too did nadir BW and BCS, and BW and BCS loss to nadir, respectively. With the exception of BCS nadir, BCS lost to nadir, and time (in days) taken to reach nadir BW and BCS, the interaction between BW at first calving and parity was associated with all of the BW and BCS performance traits (P<0.05).

Table 7.4: Association between Body Weight (BW) at first calving (kg), and BW and BCS performance traits.

	BW at first calving (kg)					Pr > F
	≤493	494-515	516-550	≥551	S.E.	
60-day BW (kg)	473.6	485.9	497	521	3.3	<0.001
305-day BW (kg)	505.3	509.3	518	534	3.3	<0.001
60-day BCS (units)	2.91	2.95	3.0	3.1	0.02	<0.001
305-day BCS (units)	2.85	2.86	2.9	2.9	0.02	<0.001
Nadir BW (kg)	455.8	463.2	472	490	3.4	<0.001
Nadir BCS (units)	2.71	2.73	2.8	2.8	0.02	<0.001
Weight loss to nadir (kg)	25.3	35.9	42	53	2.0	<0.001
Time to nadir BW (days)	50.2	49.6	49.9	48.4	2.02	0.856
BCS loss to nadir (units)	0.33	0.37	0.4	0.40	0.02	0.017
Time to nadir BCS (days)	55.2	52.9	57.5	57.4	2.13	0.137

[1] BCS= Body Condition Score

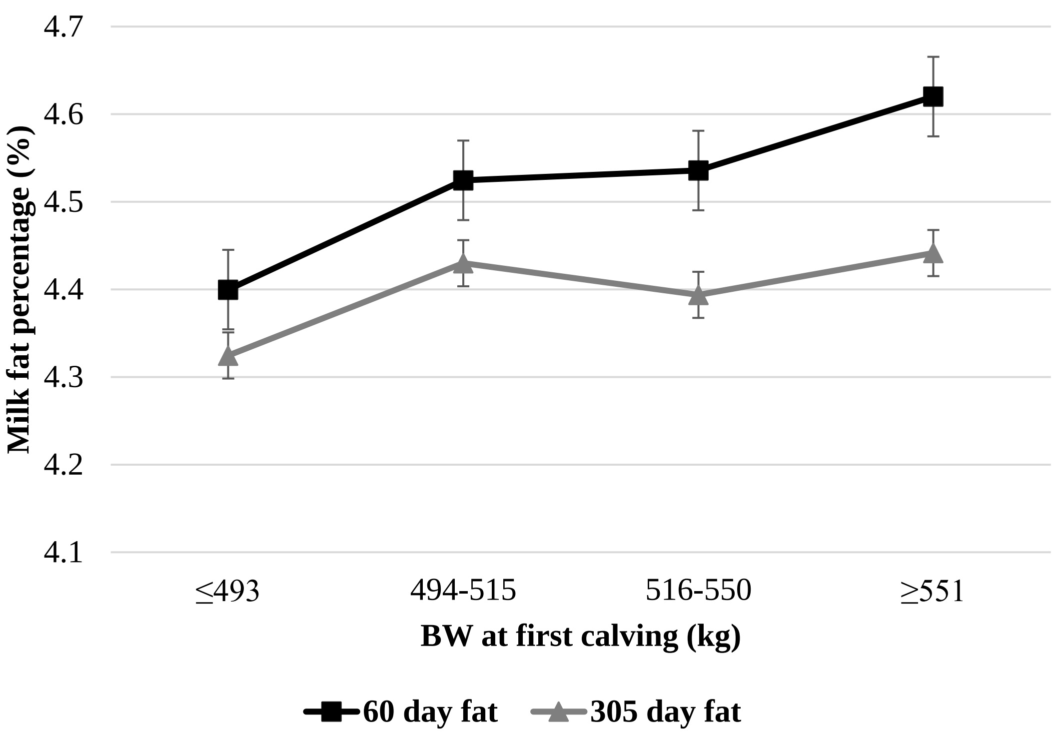


Figure 7.4: Least squares means, estimated using a linear mixed model, showing the association between body weight (BW) at first calving and 60- (squares) and 305-day (triangles) milk yields, respectively.

7.5 Discussion

Defining the best combination of AFC and BW at first calving of a seasonal-calving dairy heifer so that lifetime performance of the animal thereafter is optimized is fundamental to achieving a good return-on-investment (Dobos et al., 2001b). In many dairy production systems, AFC is one of leading determinants of replacement heifer rearing costs (Tozer and Heinrichs, 2001). Therefore, the aim is to calve young so that the heifer can start producing milk earlier, thus generate income (Gardner et al., 1977), but not so young as to be detrimental to lifetime performance (Ettema and Santos, 2004; Berry and Cromie, 2009). Heavier BW at first calving, though, may offset the adverse repercussions on performance that accompany a younger AFC (Dobos et al., 2001b). The objective of the present study was just that, to understand the association between both AFC and BW at first calving with performance but, in doing so, understand if one could compensate for the other.

7.5.1 Age at First Calving

Despite a general recommendation of an AFC of between 23 and 25 months of age for optimal economic returns (Ettema and Santos, 2004; Boulton et al., 2017), considerable variability in the AFC among dairy heifers has been reported (Pirlo et al., 2000; Ettema and Santos, 2004; Boulton et al., 2017). Such variability may be a function of the calving system in operation; in systems where calving occurs year round, heifers may be reared intensively to achieve puberty earlier (Abeni et al., 2018) and thus calve younger (Van Amburgh et al., 1998). Intensive feeding of heifers is easier in confinement systems as TMR of consistently good quality is offered throughout the rearing period (Washburn et al., 2002). In contrast, manipulation of the AFC in seasonal calving systems is limited by seasonal breeding (Berry et al., 2013) owing to the competitive advantage of pasture-based systems (Hanrahan et al., 2017). If a heifer fails to become pregnant during her first breeding season, she will not be served for several months, thus extending her non-productive lifespan. This observation is substantiated by previous research on the frequency distribution of AFC on Irish dairy farms, where two peaks at approximately 24 and 36 months of age were documented (Berry and Cromie, 2009; ICBF, 2019).

The median AFC in the present study was 731 days of age with 50% of the heifers calving for the first time between 715 and 747 days of age (i.e. an inter-quartile range of 32 days). The median AFC in the present study was only, on average, 16 (Berry and Cromie, 2009) and 26 days (Mee et al., 2011) younger than studies from commercial Irish herds.

Nevertheless, the variability in AFC in those studies was multiples of that in the present study with inter-quartile ranges of 53 (Berry and Cromie, 2009) and 170 days (Mee et al., 2011). Furthermore, Eastham et al. (2018) reported a median AFC in commercial UK herds of 28 months, with only 47% of heifers calving for the first time between 24 and 30 months of age. Atashi et al. (2021) reported a median AFC of 750 days of heifers reared in confinement at an Iranian breeding facility, with 44% of heifers calving for the first time between 690 and 750 days of age. The mean (standard deviation) AFC of Holstein heifers also reared in confinement, but this time on commercial herds in California, was 726 (50.2) days of age (Ettema and Santos, 2004). The considerably less variability in AFC observed in the present sample population is likely a large contributing factor to the inability to detect associations with some performance traits that have been documented in other populations (Ettema and Santos, 2004; Berry and Cromie, 2009; Eastham et al., 2018). The absence of large variation in the present data may be because heifers were part of controlled studies performed in research herds where all herds adhere to a standard operating procedure of heifer rearing. Management across commercial herds is unlikely to be as consistent, thus contributing to larger variability in AFC. Hence, the results from the present study are only applicable to the age range of 21.3 to 28 months of age, and should not be extrapolated to very young and very old ages at first calving.

Although a younger AFC has previously been associated with a reduction in milk yield in HF heifers (Berry and Cromie 2009), there was no association between AFC and milk yield in the present study, nor were there associations between AFC and milk yield in subsequent lactations. In the study undertaken by Berry and Cromie (2009), AFC ranged from between 20 months of age to 38 months of age; less than 1% of heifers in the present dataset calved between 20 and 22 months, while all of the heifers in the present study calved at < 28 months of age. In previous research, the negative associations between a younger AFC and milk production may have been attributable to a lighter BW at first calving in early calving heifers (Pirlo et al., 2000). In the present study, there was a wide range in BW within each of the AFC strata, which may explain the lack of associations between AFC and milk yield. This highlights the variation in BW at first calving across pasture-based dairy farms; the attainment of weight-for-age targets (Troccon, 1993) throughout the rearing period will produce a more uniform herd, and as such, may prove easier to manage.

An increase in AFC in the present study was associated with an increase in milk fat and protein percentages, with the exception of the oldest AFC stratum (i.e., AFC ≥769 days), who observed a slight reduction. This association persisted in both the second and third lactations, indicating that there may be long-lasting implications of a younger AFC on MS percentage (Froidmont et al. 2013). Although the associations were not significant, increasing the BW at first calving of the youngest AFC stratum heifers improved 60- and 305-day milk fat percentages, and 305-day protein percentage. Although the interaction between AFC, BW at first calving and parity was associated with mean 60-day milk protein percentage, the pattern was inconsistent. The reported associations between AFC and milk protein percentage were also largely contradictory in previous research (Pirlo et al., 2000; Ettema and Santos, 2004). Optimum milk fat and protein percentages were achieved by heifers in the median AFC strata i.e., when a heifer calved for the first time aged between 724 and 768 days of age. A possible explanation for the pattern in milk fat and protein percentages may be due to the different abilities of young and old heifers to ingest pasture and concentrates, which can influence milk composition thereafter (Pirlo et al., 2000).

Unsurprising in a seasonal calving system (Dillon et al., 1995; Berry and Cromie, 2009; Butler and Herlihy, 2012) where the breeding season begins on a fixed date each year (Berry and Buckley, 2016), the youngest AFC heifers had a longer interval between calving and first service thereafter. Younger heifers have previously been cited as having a favorable fertility performance (Brickell et al., 2009b). However, although the association was not significant, when age and BW were considered together, the heaviest heifers in the youngest strata appeared to have the longest CFS. This indicates that it took longer for them to show signs of heat, and although the association was not significant, it was prominent in the first parity, although it was also evident in parities two and three to a lesser extent. Longer intervals (i.e., > 85 days) between calving and first service may be detrimental to productivity because they nudge the optimum calving interval of 365 days (Esslemont et al., 2001) further out of reach.

7.5.2 Body Weight at First Calving

The mean BW at first calving in the present study (469±47.7 kg) was similar to that of pasture-based HF heifers in New Zealand (448±37.7 kg; Handcock et al., 2018), but considerably lighter than heifers reared on an Australian research farm (546 (113.8) kg; Dobos et al., 2001a). Heifers in the Dobos et al. (2001a) study were reared to achieve a target BW at first calving of 520-550 kg, which had been specified by McLean and Freeman (1996) for Australian HF heifers. Although heavier heifers at first calving have superior milk production (Dobos et al., 2001a; Archbold et al., 2012), rearing a heavier heifer (to achieve the same AFC) is also more expensive (Boulton et al., 2017).

Consistent with previous research (Hoffman, 1997; Macdonald et al., 2005; McNaughton and Lopdell, 2013), in the present study, a heavier BW at first calving, at the same AFC, was beneficial in terms of milk yield. Although the association was most pronounced in the first lactation, increasing BW at first calving also benefitted milk yield in subsequent lactations. Interestingly, when the associations between milk yield and BW at first calving were considered both with and without AFC in the model, the difference between values for milk yield were negligible (i.e., ranging from -5 to 8.5 litres), this suggests that the influence of AFC on milk yield was minimal. The associations between BW at first calving and MS were slightly more complex; while there were no associations between BW at first calving and milk protein percentages, consistent with Roche et al. (2007b), there were associations between BW at first calving and milk fat percentages thereafter. The lightest BW at first calving strata had the lowest milk fat percentages in parities one, two and three, although the associations were not as pronounced in the latter parities. The fat profile of milk is particularly susceptible to dietary changes (O'Callaghan et al., 2019); therefore, it is surprising that the association between milk fat percentage and BW at first calving persisted in subsequent lactations. The findings demonstrate the potential of a heavier BW at first calving to negate the suboptimal milk fat production that accompany a younger AFC.

Body weight at first calving was associated with the incidence of dystocia in the present study such that 10.1% of the lightest BW at first calving stratum (≤ 493 kg at calving) experienced dystocia, compared to an incidence of ≤ 6.2% in the heavier BW at first calving strata (> 494 kg at first calving). Similar to Mee et al. (2011), who reported that primiparae were more likely to experience dystocia, the incidence of dystocia in the present study was higher in parity one heifers (9.8%) than in heifers in consecutive parities (≤ 3.8%), with the lightest BW at first calving stratum in the first parity accounting for the highest proportion of the dystocia cases (4.3%). Consistent with Erb et al. (1985) increasing the BW at first calving in the present study minimized the risk of dystocia. Furthermore, findings in the present study indicate that heifers in the lightest BW at first calving strata were not susceptible to dystocia in successive parities. A case of dystocia may cost between €233 and €930 (Berry et al., 2019). Therefore, rearing a heifer to have a heavier BW at first calving, by achieving the weight-for-age targets outlined by Troccon (1993), will reduce the risk of dystocia, and thus the costs associated with calving difficulty (Dematawena and Berger, 1997; Berry et al., 2019). Consistent with Wathes et al. (2008) and Costa et al. (2021), heavier heifers at first calving in the present study also required fewer services to conceive. Therefore, increasing BW at first calving may be used to reduce the number of services required to become pregnant. Although the association was not significant, the heavier BW at first calving heifers (≥516 kg) also required fewer services to conceive in the second parity, however, the pattern in parity three was inconsistent. The difference in the number of services required by heifers weighing 516-550 kg, and ≥551 kg at first calving was negligible (0.02 services), therefore at a cost of €4.56/cow/year per 0.1 additional inseminations (Shalloo et al., 2014), rearing a heifer to calve at ≥ 551 kg will cost more (Boulton et al., 2017) without further benefit to fertility performance.

A heavier heifer at first calving was heavier, and more conditioned for the remainder of the lactation; the BW and BCS response to an increase in BW at first calving was almost linear in parity one. Although a weak linear relationship between BW at calving and BW and BCS thereafter was also noticeable in parity two, by parity three, the difference in BW was negligible. Body weight and BCS throughout the lactation are important determinants of milk production (Roche et al., 2007b) so should therefore be optimized. Furthermore, as BW at first calving increased, BW and BCS loss between calving and nadir were almost linear in the first parity; however, this was not the case in parity two and parity three. Excessive BW and BCS loss indicates the mobilization of body reserves, which has been reported to impede the fertility performance (Buckley et al. 2003) and milk production (Berry et al., 2007b) of HF heifers.

7.6 Conclusion

While AFC and BW at first calving were associated with production performance thereafter, the findings presented are confined to the limits of AFC and BW at first calving; AFC and BW at first calving beyond these limits may contribute to a different result. Although BW at first calving had a greater influence on production thereafter than AFC, rearing a heifer to be heavier at first calving requires higher input costs, so may not be economically viable unless achieved by increasing the proportion of grazed grass in the diet. Heifers that had a median age (between 738 and 768 days of age) and BW at first calving (between 516 and 550 kg) performed most favourably in terms of calving performance, milk production, fertility performance and BW and BCS, however, the optimum combination of age and BW at first calving is a function of milk price and costs of production, and should therefore be farm specific.

Chapter 8: Summary, Implications and Further Research

Until recently, there had been limited research on the rearing of pasture-based dairy heifers; it was therefore assumed that their management and target weights should be comparable to that of their counterparts reared in confinement. However, this may not be the case due to differences in feed, and consequently, growth throughout the rearing period (Handcock et al., 2021). It became evident that further research was warranted to truly understand the mechanisms of pasture-based heifer growth throughout the rearing period. The objective of this thesis was, therefore, to investigate different aspects of performance in pasture-based heifers reared under contrasting management systems, and by creating a series of equations, provide farmers with tools to monitor, and therefore optimize the DMI, growth and fertility performance of their heifers.

As there is currently no optimum pasture-based heifer rearing strategy, and because heifer growth varies from farm to farm (Archbold et al., 2012; Bazeley et al., 2016), all Chapters in this thesis incorporated contrasting heifer rearing management systems, i.e., different weaning ages and different post-weaning feeding regimes. Treatment in the pre and the post-weaning period has the potential to influence growth (Le Cozler et al., 2010) and thus future performance (Brickell et al., 2009b; Le Cozler et al., 2010; Davis Rincker et al., 2011) of the heifer. The aim of this thesis was to quantify the associations between management during the rearing period and factors influencing growth. Breed was also included as the Irish national dairy herd is currently predominated by three main breeds; Holstein, Friesian, and JE, which accounted for 89.1, 5.6, and 4.3%, respectively, of dairy inseminations in 2019 and 2020 (ICBF, 2020). While HF are the mainstay of the Irish national dairy herd, JE genetics, both in their own right (Prendiville et al., 2011a) and as a cross with HF (Coffey et al., 2017), are increasingly contributing to the Irish dairy herd due to their superior MS (Prendiville et al., 2011b) and production efficiency (Lembeye et al., 2016). Investigating interactions between management strategy and breed provide information to guide decisions on how best to optimize replacement heifer growth.

Optimizing replacement heifer growth is generally accomplished by attaining weight-for-age targets (Troccon, 1993). These targets ensure that, by growing heifers at a constant rate throughout the rearing period, growth and thus, performance will be optimized. Nonetheless, Handcock et al. (2021) reported that as long as target BW at breeding is achieved (i.e., the heifer has gained sufficient BW to achieve puberty), that the growth trajectory between six and 15 months of age would not have a negative impact on first lactation milk production. This finding by Handcock et al. (2021) has positive practical significance for heifers with a seasonal pattern of growth, such as those in Ireland, and provides justification for the different management systems implemented in the present study. However, it is clear from previous research that many pasture-based heifers are failing to achieve target BW at breeding (McNaughton and Lopdell, 2012; Handcock et al., 2016). This may be because farmers are simply not monitoring heifer BW; less than 5% of New Zealand heifers had a BW recorded before calving (McNaughton and Lopdell, 2012), but it may also be because heifer DMI at pasture has not previously been investigated. Knowledge of heifer DMI at different ages ensures sufficient pasture is offered, thus making certain heifers are not underfed. Furthermore, despite BW at breeding often being cited as the most important target, if, at breeding, a heifer is found to be below target, it is then too late to rectify BW. Therefore, additional weight-for-age targets can benefit pasture-based dairy heifers by ensuring that BW prior to breeding is optimized. This is the first study to establish the DMI of pasture-based dairy heifers, and it is one of the first to quantify pasture-based heifer growth under different management strategies. Heifer DMI and BW are intertwined, both of which were found to be more susceptible to post-weaning feeding regimes than weaning age. This finding is important as it demonstrates that pasture allocation and consequently, BW may be manipulated in the post-weaning period to ensure that heifers have gained the BW necessary to become pubertal prior to the commencement of the breeding season. Nevertheless, a possible limitation of the present thesis is the influence of concentrate on heifer DMI in the first grazing season. It is difficult to measure the individual concentrate intake of heifers in a pasture-based system, and as such, heifer DMI in the present study was calculated by summing group average concentrate DMI and individual grass DMI. Although a limitation in the present thesis, the inability to measure individual concentrate DMI in pasture-based heifers may form the basis for further research on this topic.

Consistent with pasture-based HF and JE cows (Prendiville et al., 2011a), differences in DMI and BW were also identified in pasture-based HF and JE heifers. Similar to that observed in the JE heifers in the present study, JE cows had a higher capacity for feed intake, which is likely attributable to grazing behaviour, in particular, increased bite rate, intake rate, and time spent grazing on a per unit of BW basis (Prendiville et al., 2010). The use of technology to establish the grazing behaviour of pasture-based HF and JE heifers reared under different strategies would have greatly enhanced the findings in chapter 3; such measurements should therefore be incorporated into future research on pasture-based heifer DMI. A higher intake capacity may contribute to increased production efficiency, which, in the lactating herd, is characterized by superior MS production per unit of BW and per unit of DMI (Prendiville et al., 2009; Beecher et al., 2014). Increased production efficiency in the rearing period would signify higher BW gain per unit of DMI (Akins et al., 2016); however, it was beyond the scope of the present study to substantiate this claim in pasture-based dairy heifers, and as such, could be considered a limitation of the present study. However, information on the feed efficiency of pasture-based dairy heifers would be advantageous, and so, should be the focus of further research.

In addition to the differences in the DMI of pasture-based HF and JE heifers alluded to in the previous paragraph, there was also an effect of breed on the attainment of weight-for-age targets, particularly at six months, when 40.3 and 24.6% of HF and JE, respectively, had attained target weight. However, the attainment of weight-for-age targets was similar for HF and JE thereafter. This study has established that although the attainment of weight-for-age targets at six and 15 months was suboptimal (approximately 46 and 47% of all heifers were either at or ahead of target at six and 15 months, respectively), different management strategies (i.e., 12wH) may be used to ensure that a greater proportion of heifers have achieved weight-for-age targets. However, using the equations proposed in Chapter 4 to create additional targets will complement the management of pasture-based HF and JE heifers and ensure that they have achieved target weight at breeding, which is of particular importance in systems that impose seasonal breeding, such as that in Ireland. Although there are key times for weighing heifers such as at birth, at weaning, at breeding, and prior to calving (Bazeley et al., 2016), this may not be achievable, particularly on a pasture-based dairy farm where the heifers are often reared away from the milking platform and may not be subject to regular monitoring. The equation proposed in Chapter 4 may be used to create additional weight-for-age targets at every stage of the rearing period; this will be of practical significance to pasture-based dairy farmers so that weighing can be aligned with different husbandry tasks to minimize inconvenience and optimize time. The equations created in Chapters 3 and 4 will ultimately provide pasture-based dairy farmers with the tools necessary to firstly identify heifer DMI, which will optimize pasture allocation and thus utilization, and secondly to optimize heifer growth throughout the rearing period by achieving weight-for-age targets.

It is apparent that monitoring heifer growth is essential for a rearing strategy to be successful. Although weighing is the easiest and most accurate measurement of heifer growth (Dingwell et al., 2006), it is not clear how many farmers are actually weighing their youngstock. As previously mentioned, very few heifers in New Zealand have BW records prior to calving (McNaughton and Lopdell, 2012), while information on the proportion of Irish dairy farmers weighing their heifers was unavailable. A possible explanation may be that Irish dairy farmers are hesitant to adopt new technologies, i.e., electronic weighing scales (Lukuyu et al., 2016). Nevertheless, it is also possible to monitor the growth of heifers using LBM (Heinrichs et al., 1992). Findings in Chapter 5 indicate that although there were different mechanisms in the growth pattern of heifer frame size to that of BW gain, similar to that found in Chapter 4, there was also a greater effect of post-weaning feeding regime on LBM than that of weaning age. In Chapters 5 and 6, it was established that, in the absence of a scale, LBM might instead be used to monitor growth. Furthermore, the creation of equations to predict the BW of heifers using a series of LBM will allow farmers to benchmark their heifers' growth against that of the weight-for-age targets. Although such equations have previously been created in confinement systems of heifer rearing (Heinrichs et al., 1992; Dingwell et al., 2006; Silva et al., 2021), it was established in Chapter 4 that the growth trajectory of pasture-based heifers is sigmoidal in shape and therefore, equations to predict BW from LBM must be aligned with the system within which heifers are reared, e.g., pasture-based or confinement. The proposed equations have high prediction accuracy and incorporate a variety of LBM, which may be of benefit to pasture-based dairy farmers as they can select the LBM most suited to their facilities.

Poor growth rates in the rearing period, which are possible if growth is not closely monitored, mean that many heifers never fulfil their potential. In order to achieve optimal lifetime performance, it is important for heifers to be well-grown and achieve weight-for-age targets throughout the rearing period (Le Cozler et al., 2008). Poorly grown heifers may also suffer reproductive inefficiency (Wathes et al., 2008). An interesting finding of Chapter 5 was that heifers grown at a constant rate, i.e., those that were weaned early and subsequently offered a low feeding regime, and those that were weaned late and subsequently offered a high feeding regime, had improved fertility performance. Consistent with Curtis et al. (2018) and Davis Rincker et al. (2011), heifers fed an intensive diet in the pre-weaning period were more likely to exhibit pre-pubertal estrus activity. A slight decline in reproductive efficiency was observed in heifers that were ahead of target weight at breeding; this corroborates the study by Archbold et al. (2012). However, this study may be limited by both the sample size and the reliance on routine fertility observations to determine the fertility performance of pasture-based dairy heifers. The binary nature of reproductive data in the present study requires a confidence interval of >10% to declare a significant difference between treatment groups, as such, further research that incorporates either a larger sample size or more in-depth fertility measurements may be required to support the conclusions drawn about the fertility performance of heifers. Findings in chapters 3, 4, 5 and 6 advocate that heifers weaned later and offered a high feeding regime post-weaning will have improved growth and fertility performance, however, the impact of rearing strategy on eventual milk production was not investigated in the present study. Although this may be considered a limitation, it also provides direction for further research on the association between rearing strategy and milk production of pasture-based heifers.

A calving event provides a connection between the rearing period and the lactating herd for a heifer. In 2020, only 71% of heifers in Ireland calved for the first time, aged between 22 and 26 months (ICBF, 2020). Achieving target AFC in pasture-based dairy heifers may be limited by inadequate monitoring of heifer growth, such that if a heifer has not gained sufficient weight throughout the rearing period to achieve puberty prior to the seasonal breeding season, conception, and consequently, calving may be delayed. Heifers that calve late in the season are more likely to be culled (Mousel et al., 2014); therefore, the importance of monitoring heifer growth cannot be over-emphasized. The age at which a heifer calves signifies the beginning of the repayment of heifer rearing costs (Boulton et al., 2017); it is, therefore, unsurprising that a younger AFC is recommended, as it will reduce the non-productive period. However, it has been cited that a younger AFC will be accompanied by a reduction in milk production (Berry and Cromie, 2009). The findings in Chapter 7 indicate that, as long as heifers are not too young (≤723 days of age) or too old (≥769 days of age), this is not always the case. The weight at which heifers calve was found to have a greater effect on production in the lactating herd than that of AFC. Furthermore, the present study has agreed with that reported by Dobos et al. (2001); increasing BW at calving can negate the unfavourable associations that may accompany a younger AFC. Optimum production was achieved when a heifer calved for the first time aged between 738 and 768 days and weighing between 516 and 550 kg post-calving, i.e., if a heifer was heavier (≥551 kg) and older (≥769 days of age) at first calving, production thereafter was impeded. However, the findings in chapter 7 may be limited by the lack of variability in AFC and BW at calving relative to the variation reported in similar studies

(Berry and Cromie, 2009; Mee et al., 2011). Despite this limitation, the findings in chapter 7 still highlight the importance of monitoring heifer BW throughout the rearing period.

In conclusion, studies described in this thesis have:

1. Quantified the DMI of pasture-based HF and JE heifers reared under different management systems throughout the rearing period. Confirmed that there are differences in both the total DMI and intake capacity of pasture-based HF and JE heifers. Found that DMI is sensitive to feed management throughout the rearing period and, as such, may be manipulated by varying concentrate supplementation and pasture allowance to ensure that weight-for-age targets are achieved. Formulated an equation to predict the DMI of pasture-based dairy heifers using BW.

2. Determined, through the creation of an equation to predict the growth trajectory of heifers, that pasture-based heifer growth is not linear. Observed that heifer BW was receptive to post-weaning feed management; therefore, different rearing strategies may be implemented to optimize heifer growth throughout the rearing period. Established that existing weight-for-age targets are achievable; however, the use of the proposed equation to create additional targets may complement the management of pasture-based heifers and ensure that they have gained the BW necessary to achieve puberty prior to the breeding season.

3. Reported that LBM are also responsive to changes in the post-weaning feed management of pasture-based heifers. Presented that heifers grown at a constant rate had improved reproductive efficiency. In contrast, heifers that were ahead of weight-for-age targets at breeding had a poor fertility performance thereafter.

4. Found that LBM were accurate predictors of pasture-based heifer BW. Created a series of equations that offer farmers the opportunity to monitor heifer growth in the absence of

a scale, with the equation based on BV proposed as the most innovative predictor of heifer BW.

5. Evaluated the associations between AFC, BW at first calving, and production thereafter. Reported that a heavier BW at first calving offset the negative effect of a younger AFC on milk production. Concluded that optimum performance was achieved when a HF heifer was 738-768 days of age and weighed 516-550 kg at first calving. Observed negative associations in heifers that were over-weight at first calving, thus verifying that weight-for-age targets should be adhered to throughout the rearing period.

In summary, these studies indicate that there are various mechanisms throughout the rearing period that have the potential to influence heifer growth and performance thereafter. Establishing the DMI of pasture-based heifers will facilitate the accurate allocation of pasture and ensure that the competitive advantage of a pasture-based system is exploited. Furthermore, achieving the weight-for-age targets outlined in the present study will optimize heifer BW and LBM, and consequently, performance in the lactating herd. Collectively, these studies contribute to the understanding of pasture-based heifer rearing and will be a useful resource when generating further research in this area.

Chapter 9: References

Abeni, F., F. Petrera, and Y. Le Cozler. 2018. Effects of feeding treatment on growth rates, metabolic profiles and age at puberty, and their relationships in dairy heifers. Animal 13(5):1020-1029.

Abrahamse, P., J. Dijkstra, B. Vlaeminck, and S. Tamminga. 2008. Frequent allocation of rotationally grazed dairy cows changes grazing behaviour and improves productivity. Journal of Dairy Science 91(5): 2033-2045.

Agri-Food and Biosciences Institute (AFBI), Department of Agriculture, Food and the Marine (DAFM) 2017. All-Island Animal disease surveillance report 2016. Retrieved on 30 October 2021 from https://www.afbini.gov.uk/sites/afbini.gov.uk/files/publications/aiadsr2015_30-11-16%20LR_Designer%204.pdf

AHI. 2016. Getting your dairy heifer calves to target weight. Animal Health Ireland bulletin May 2016. https://animalhealthireland.ie/assets/uploads/2021/06/AHI-Bulletin-April-2021-Revised-2021.pdf?dl=1

AHI. 2021. Technical notes on calf milk replacers (CMR) for rearing dairy replacement heifer calves. CalfCare leaflet series. www.AnimalHealthIreland.ie.

Akins, M. S. 2016. Dairy heifer development and nutrition management. Veterinary Clinics: Food Animal Practice 32(2):303-317.

Akins, M., M. Cavitt, M. Hagedorn, S. Mills-Lloyd, T. Kohlman, R. Sterry, L. Binversie, A. Bjurstrom, G. Blonde, and J. Clark. 2017. Economic Costs and Labour Efficiencies Associated with Raising Dairy Calves for Operations Using Individual or Automated Feeding. University of Wisconsin Extension: Madison, WI, USA 8.

Albertí, P., B. Panea, C. Sañudo, J. Olleta, G. Ripoll, P. Ertbjerg, M. Christensen, S. Gigli, S. Failla, and S. Concetti. 2008. Live weight, body size and carcass characteristics of young bulls of fifteen European breeds. Livestock Science 114(1):19-30.

Alvarez-Hess, P. S., M. L. Douglas, M. M. Wright, N. Norbu, K. Giri, W. J. Wales, J. L. Jacobs, and M. J. Auldist. 2021. Effects of herbage mass and herbage allowance on bite mass of grazing dairy cows. Animal Feed Science and Technology 278:115011.

Anderson, K. L., T. G. Nagaraja, J. L. Morrill, T. B. Avery, S. J. Galitzer, and J. E. Boyer. 1987. Ruminal Microbial Development in Conventionally or Early-Weaned Calves1. Journal of Animal Science 64(4):1215-1226.

Appleby, M. C., D. M. Weary, and B. Chua. 2001. Performance and feeding behaviour of calves on ad libitum milk from artificial teats. Applied Animal Behaviour Science 74(3):191-201.

Archbold, H., L. Shalloo, E. Kennedy, K. Pierce, and F. Buckley. 2012. Influence of age, body weight and body condition score before mating start date on the pubertal rate of maiden Holstein-Friesian heifers and implications for subsequent cow performance and profitability. Animal: an International Journal of Animal Bioscience 6(7):1143.

Atashi, H., A. Asaadi, and M. Hostens. 2021. Association between age at first calving and lactation performance, lactation curve, calving interval, calf birth weight, and dystocia in Holstein dairy cows. PloS one 16(1):e0244825-e0244825.

Atkins, N. E., E. C. Bleach, and L. A. Sinclair. 2018. Periparturient and early lactation performance and metabolism of replacement Holstein-Friesian heifers out-wintered on fodder beet or perennial ryegrass compared with winter housing. Grass and Forage Science 73(4):828-840.

Atkins, N. E., K. Walley, and L. A. Sinclair. 2020. Commercial practice of out-wintering dairy heifers in Great Britain. Journal of New Zealand Grasslands 82.

Bailey, T. L. and J. M. Murphy. 2009. Monitoring dairy heifer growth.

Barnes, A. P., H. McCalman, S. Buckingham, and S. Thomson. 2013. Farmer decision-making and risk perceptions towards outwintering cattle. Journal of Environmental Management 129:9-17.

Barrier, A. and M. Haskell. 2011. Calving difficulty in dairy cows has a longer effect on saleable milk yield than on estimated milk production. Journal of dairy science 94(4):1804-1812.

Barry, J., E. A. Bokkers, D. Berry, I. J. de Boer, J. McClure, and E. Kennedy. 2019. Associations between colostrum management, passive immunity, calf-related hygiene practices, and rates of mortality in preweaning dairy calves. Journal of dairy science 102(11):10266-10276.

Barry, J. 2020. Colostrum feeding and calf welfare assessment: the first steps to a better future. Thesis: Wageningen University. https://edepot.wur.nl/509741

Bartlett, K., F. McKeith, M. VandeHaar, G. Dahl, and J. Drackley. 2006. Growth and body composition of dairy calves fed milk replacers containing different amounts of protein at two feeding rates. Journal of Animal Science 84(6):1454-1467.

Baumwart, A. L. 1976. Absorption of immunoglobulins from colostrum by newborn calves. Oklahoma State University.

Bazeley, K. J., D. C. Barrett, P. D. Williams, and K. K. Reyher. 2016. Measuring the growth rate of UK dairy heifers to improve future productivity. Veterinary journal 212:9-14.

Beecher, M., F. Buckley, S. M. Waters, T. Boland, D. Enriquez-Hidalgo, M. Deighton, M. O'Donovan, and E. Lewis. 2014. Gastrointestinal tract size, total-tract digestibility, and rumen microflora in different dairy cow genotypes. Journal of dairy science 97(6):3906-3917.

Beecher, M., D. Hennessy, T. Boland, M. McEvoy, M. O'Donovan, and E. Lewis. 2015. The variation in morphology of perennial ryegrass cultivars throughout the grazing season and effects on organic matter digestibility. Grass and Forage Science 70(1):19-29.

Bell, J. 1958. Raising dairy calves without whole milk. Canadian Journal of Animal Science 38(2):103-108.

Benetton, J., H. Neave, J. Costa, M. Von Keyserlingk, and D. Weary. 2019. Automatic weaning based on individual solid feed intake: Effects on behaviour and performance of dairy calves. Journal of dairy science 102(6):5475-5491.

Berge, A., T. Besser, D. Moore, and W. Sischo. 2009. Evaluation of the effects of oral colostrum supplementation during the first fourteen days on the health and performance of preweaned calves. Journal of Dairy Science 92(1):286-295.

Berry, D. P., F. Buckley, P. Dillon, R. D. Evans, M. Rath, and R. F. Veerkamp. 2003. Genetic Relationships among Body Condition Score, Body Weight, Milk Yield, and Fertility in Dairy Cows. Journal of Dairy Science 86(6):2193-2204.

Berry, D., L. Shalloo, A. Cromie, V. Olori, and P. Amer. 2005. Economic breeding index for dairy cattle in Ireland. Irish Cattle Breeding Federation: Bandon, Cork.

Berry, D. P., K. A. Macdonald, J. W. Penno, and J. R. Roche. 2006. Association between body condition score and live weight in pasture-based Holstein-Friesian dairy cows. Journal of dairy research 73(4):487-491.

Berry, D., J. Lee, K. Macdonald, K. Stafford, L. Matthews, and J. Roche. 2007a. Associations among body condition score, body weight, somatic cell count, and clinical mastitis in seasonally calving dairy cattle. Journal of dairy science 90(2):637-648.

Berry, D. P., F. Buckley, and P. Dillon. 2007b. Body condition score and live-weight effects on milk production in Irish Holstein-Friesian dairy cows. Animal 1(9):1351-1359.

Berry, D., J. Lee, K. Macdonald, and J. Roche. 2007c. Body condition score and body weight effects on dystocia and stillbirths and consequent effects on post calving performance. Journal of Dairy Science 90(9):4201-4211.

Berry, D. and A. Cromie. 2009. Associations between age at first calving and subsequent performance in Irish spring calving Holstein–Friesian dairy cows. Livestock Science 123(1):44-54.

Berry, D. P., A. Cromie, F. Buckley, S. Butler, and S. Cummins. 2012. Breeding for fertility in Irish dairy cows. Proc. Dairy Cow Fertility Reproductive performance for efficient pasture-based systems.

Berry, D. P., M. P. Coffey, J. E. Pryce, Y. de Haas, P. Løvendahl, N. Krattenmacher, J. J. Crowley, Z. Wang, D. Spurlock, K. Weigel, K. Macdonald, and R. F. Veerkamp. 2014. International genetic evaluations for feed intake in dairy cattle through the collation of data from multiple sources. Journal of Dairy Science 97(6):3894-3905.

Berry, D. P., F. Buckley, and S. T. Butler. 2015. Reducing replacement cost on Irish dairy farms. Moorepark '15 Irish dairying sustainable expansion. Accessed on 10 September 2021. Pages 23-30. https://www.teagasc.ie/media/website/publications/2015/Irish_Dairying-Sustainable_Expansion_Moorepark15.pdf

Berry, D. P. and F. Buckley. 2016. Teagasc Dairy Manual: Dairy Cow Breeding. Accessed on 10 September 2021. https://www.teagasc.ie/media/website/publications/2016/Dairy-Manual-Section7.pdf

Berry, D., P. Amer, R. Evans, T. Byrne, A. Cromie, and F. Hely. 2019. A breeding index to rank beef bulls for use on dairy females to maximize profit. Journal of dairy science 102(11):10056-10072.

Bertics, S. J., R. R. Grummer, C. Cadorniga-Valino, and E. E. Stoddard. 1992. Effect of prepartum dry matter intake on liver triglyceride concentration and early lactation. Journal of dairy science 75(7):1914-1922.

Besser, T., A. Garmedia, T. McGuire, and C. Gay. 1985. Effect of colostral immunoglobulin G1 and immunoglobulin M concentrations on immunoglobulin absorption in calves. Journal of Dairy Science 68(8):2033-2037.

Besser, T. E., C. Gay, and L. Pritchett. 1991. Comparison of three methods of feeding colostrum to dairy calves. Journal of the American Veterinary Medical Association 198(3):419-422.

Bielmann, V., J. Gillan, N. R. Perkins, A. L. Skidmore, S. Godden, and K. E. Leslie. 2010. An evaluation of Brix refractometry instruments for measurement of colostrum quality in dairy cattle. Journal of Dairy Science 93(8):3713-3721.

Bjorklund, E., B. J. Heins, and H. Chester-Jones. 2013. Whole-milk feeding duration, calf growth, and profitability of group-fed calves in an organic production system. Journal of dairy science 96(11):7363-7370.

Blome, R., J. Drackley, F. McKeith, M. Hutjens, and G. McCoy. 2003. Growth, nutrient utilization, and body composition of dairy calves fed milk replacers containing different amounts of protein. Journal of Animal Science 81(6):1641-1655.

Blum, J. W. and H. Hammon. 2000. Colostrum effects on the gastrointestinal tract, and on nutritional, endocrine and metabolic parameters in neonatal calves. Livestock Production Science 66(2):151-159.

Boulton, A. C., J. Rushton, and D. C. Wathes. 2015. A study of dairy heifer rearing practices from birth to weaning and their associated costs on UK dairy farms. Open Journal of Animal Sciences 5:185-197.

Boulton, A., J. Rushton, and D. Wathes. 2017. An empirical analysis of the cost of rearing dairy heifers from birth to first calving and the time taken to repay these costs. Animal 11(8):1372-1380.

Brickell, J., M. McGowan, and D. Wathes. 2009a. Effect of management factors and blood metabolites during the rearing period on growth in dairy heifers on UK farms. Domestic animal endocrinology 36(2):67-81.

Brickell, J. S., N. Bourne, M. M. McGowan, and D. C. Wathes. 2009b. Effect of growth and development during the rearing period on the subsequent fertility of nulliparous Holstein-Friesian heifers. Theriogenology 72(3):408-416.

Britt, J. 1992. Influence of nutrition and weight loss on reproduction and early embryonic death in cattle. Proc. American Association of Bovine Practitioners Conference proceedings (USA).

Bruinjé, T. C., J. P. Rosadiuk, F. Moslemipur, J. E. Carrelli, M. A. Steele, and D. J. Ambrose. 2019. Carryover effects of pre- and post-weaning planes of nutrition on reproductive tract development and estrus cycle characteristics in Holstein heifers. Journal of Dairy Science 102(11):10514-10529.

Buckley, F., K. O'Sullivan, J. F. Mee, R. D. Evans, and P. Dillon. 2003. Relationships among Milk Yield, Body Condition, Cow Weight, and Reproduction in Spring-Calved Holstein-Friesians. Journal of Dairy Science 86(7):2308-2319.

Buckley, F., P. Dillon, S. Crosse, F. Flynn, and M. Rath. 2000. The performance of Holstein Friesian dairy cows of high and medium genetic merit for milk production on grass-based feeding systems. Livestock Production Science 64(2-3):107-119.

Burke, J., G. Waghorn, and A. Chavez. 2002. Improving animal performance using forage-based diets. Pages 267-272 in Proc. Proceedings- New Zealand society of animal production. New Zealand Society of Animal Production; 1999.

Burns, G., T. Gilliland, D. Grogan, S. Watson, and P. O'Kiely. 2013. Assessment of herbage yield and quality traits of perennial ryegrasses from a national variety evaluation scheme. The Journal of Agricultural Science 151(3):331-346.

Bush, L. J. and T. E. Staley. 1980. Absorption of Colostral Immunoglobulins in Newborn Calves1. Journal of Dairy Science 63(4):672-680.

Butler, J. E. 1969. Bovine immunoglobulins: A review. Journal of Dairy Science 52(12):1895-1909.

Butler, S. and M. Herlihy. 2012. Use of controlled breeding programmes in seasonal calving systems. in Proc. Dairy Cow Fertility Reproductive performance for efficient pasture-based systems, Rochestown Park Hotel and Teagasc, Moorepark Research Centre, Cork, Ireland. Accessed on 10 September 2021. Pages 95-99. https://www.teagasc.ie/media/website/publications/2010/Dairy_Cow_Fertility_Proceedings_2012.pdf

Butler, S., M. Herlihy, D. P. Berry, and M. G. Diskin. 2012. Use of synchronization in dairy cows to maximize submission rates. Accessed on 12 September 2021. https://www.teagasc.ie/media/website/publications/2011/Use-of-AI_5672-B.pdf

Butler, S. T. 2013. Genetic control of reproduction in dairy cows. Reproduction, Fertility and Development 26(1):1-11.Butler, W. 2005. Nutrition, negative energy balance and fertility in the postpartum dairy cow. Cattle practice 13:13-18.

Butler, W. R. and R. D. Smith. 1989. Interrelationships between Energy Balance and Postpartum Reproductive Function in Dairy Cattle. Journal of Dairy Science 72(3):767-783.

Byerley, D., R. Staigmiller, J. Berardinelli, and R. Short. 1987. Pregnancy rates of beef heifers bred either on puberal or third estrus. Journal of animal science 65(3):645-650.

Byrne, C., S. Fair, A. English, D. Johnston, P. Lonergan, and D. Kenny. 2017. Effect of milk replacer and concentrate intake on growth rate, feeding behaviour and systemic metabolite concentrations of pre-weaned bull calves of two dairy breeds. Animal 11(9):1531-1538.

Canadas, E. R., M. Herlihy, J. Kenneally, J. Grant, F. Kearney, P. Lonergan, and S. Butler. 2020. Associations between postpartum phenotypes, cow factors, genetic traits, and reproductive performance in seasonal-calving, pasture-based lactating dairy cows. Journal of dairy science 103(1):1016-1030.

Carson, A., L. Dawson, M. McCoy, D. Kilpatrick, and F. Gordon. 2002. Effects of rearing regime on body size, reproductive performance and milk production during the first lactation in high genetic merit dairy herd replacements. Animal Science 74(3):553-565.

Carty, C. I., C. G. McAloon, L. O'Grady, E. G. Ryan, and F. J. Mulligan. 2020. Relative effect of milk constituents on fertility performance of milk-recorded, spring-calving dairy cows in Ireland. Journal of Dairy Science 103(1):940-953.

Castells, L., A. Bach, G. Araujo, C. Montoro, and M. Terré. 2012. Effect of different forage sources on performance and feeding behaviour of Holstein calves. Journal of Dairy Science 95(1):286-293.

CBS. 2019. Again more cattle grazing. Accessed 7 September 2021 on https://www.cbs.nl/en-gb/news/2019/48/again-more-cattle-grazing.

Chebel, R. C., F. A. Braga, and J. C. Dalton. 2007. Factors affecting reproductive performance of Holstein heifers. Animal Reproduction Science 101(3):208-224.

Chelikani, P. K., J. D. Ambrose, and J. J. Kennelly. 2003. Effect of dietary energy and protein density on body composition, attainment of puberty, and ovarian follicular dynamics in dairy heifers. Theriogenology 60(4):707-725.

Chigerwe, M., J. W. Tyler, M. K. Summers, J. R. Middleton, L. G. Schultz, and D. W. Nagy. 2009. Evaluation of factors affecting serum IgG concentrations in bottle-fed calves. Journal of the American Veterinary Medical Association 234(6):785-789.

Claffey, A., L. Delaby, N. Galvin, T. Boland, and M. Egan. 2019. The effect of spring grass availability and grazing rotation length on the production and quality of herbage and milk in early spring. The Journal of Agricultural Science 157(5):434-448.

Coffey, E. L., B. Horan, R. D. Evans, and D. P. Berry. 2016. Milk production and fertility performance of Holstein, Friesian, and Jersey purebred cows and their respective crosses in seasonal-calving commercial farms. Journal of Dairy Science 99(7):5681-5689.

Coffey, E. L., L. Delaby, S. Fitzgerald, N. Galvin, K. M. Pierce, and B. Horan. 2017. Effect of stocking rate and animal genotype on dry matter intake, milk production, body weight, and body condition score in spring-calving, grass-fed dairy cows. Journal of Dairy Science 100(9):7556-7568.

Cole, J. B. and D. J. Null. 2009. Genetic evaluation of lactation persistency for five breeds of dairy cattle. Journal of Dairy Science 92(5):2248-2258.

Compton, C. W. R. 2018. The epidemiology of culling and mortality of New Zealand dairy cows: a thesis presented in partial fulfilment of the requirements for the degree of PhD in Veterinary Epidemiology at Massey University, Manawatu, New Zealand. Massey University.

Conneely, M., D. P. Berry, R. Sayers, J. P. Murphy, I. Lorenz, M. L. Doherty, and E. Kennedy. 2013. Factors associated with the concentration of immunoglobulin G in the colostrum of dairy cows. Animal 7(11):1824-1832.

Conneely, M., D. P. Berry, J. P. Murphy, I. Lorenz, M. L. Doherty, and E. Kennedy. 2014. Effect of feeding colostrum at different volumes and subsequent number of transition milk feeds on the serum immunoglobulin G concentration and health status of dairy calves. Journal of Dairy Science 97(11):6991-7000.

Cooke, J. S., Z. Cheng, N. E. Bourne, and D. C. Wathes. 2013. Association between growth rates, age at first calving and subsequent fertility, milk production and survival in Holstein-Friesian heifers. Open Journal of Animal Sciences Vol.03No.01:12.

Costa, A., C. Boselli, and M. De Marchi. 2021. Effect of Body Weight and Growth in Early Life on the Reproductive Performances of Holstein Heifers. Agriculture 11(2):159.

Costigan, H., L. Delaby, S. Walsh, B. Lahart, and E. Kennedy. 2021. The development of equations to predict live-weight from linear body measurements of pasture-based Holstein-Friesian and Jersey dairy heifers. Livestock Science: 104693.

Coverdale, J., H. Tyler, J. D. Quigley III, and J. Brumm. 2004. Effect of various levels of forage and form of diet on rumen development and growth in calves. Journal of dairy science 87(8):2554-2562.

Cowles, K. E., R. A. White, N. L. Whitehouse, and P. S. Erickson. 2006. Growth Characteristics of Calves Fed an Intensified Milk Replacer Regimen with Additional Lactoferrin1. Journal of Dairy Science 89(12):4835-4845.

Creighton, P., E. Kennedy, L. Shalloo, T. Boland, and M. O'Donovan. 2011. A survey analysis of grassland dairy farming in Ireland, investigating grassland management, technology adoption and sward renewal. Grass and Forage Science 66(2):251-264.

Crosse, S. and P. Gleeson. 1986. Effects of pre-calving liveweight and level of concentrate feeding post-calving on the performance of first-lactation heifers. Irish Journal of Agricultural Research: 313-320.

Cummins, C., D. P. Berry, R. Sayers, I. Lorenz, and E. Kennedy. 2016. Questionnaire identifying management practices surrounding calving on spring-calving dairy farms and their associations with herd size and herd expansion. Animal 10(5):868-877.

Cummins, C., D. Berry, J. Murphy, I. Lorenz, and E. Kennedy. 2017. The effect of colostrum storage conditions on dairy heifer calf serum immunoglobulin G concentration and preweaning health and growth rate. Journal of dairy science 100(1):525-535.

Curran, J., L. Delaby, E. Kennedy, J. Murphy, T. Boland, and M. O'Donovan. 2010. Sward characteristics, grass dry matter intake and milk production performance are affected by pre-grazing herbage mass and pasture allowance. Livestock Science 127(2-3):144-154.

Curtis, G., C. McGregor Argo, D. Jones, and D. Grove-White. 2018. The impact of early life nutrition and housing on growth and reproduction in dairy cattle. PloS one 13(2):e0191687.

DairyNZ (2015). "Estimating mature liveweight for groups of dairy heifers ". Retrieved 3 August, from https://www.dairynz.co.nz/publications/farmfacts/animal-health-welfare-and-youngstock/.

Dallago, G. M., K. M. Wade, R. I. Cue, J. T. McClure, R. Lacroix, D. Pellerin, and E. Vasseur. 2021. Keeping Dairy Cows for Longer: A Critical Literature Review on Dairy Cow Longevity in High Milk-Producing Countries. Animals 11(3):808.

Davis Rincker, L. E., M. J. VandeHaar, C. A. Wolf, J. S. Liesman, L. T. Chapin, and M. S. Weber Nielsen. 2011. Effect of intensified feeding of heifer calves on growth, pubertal age, calving age, milk yield, and economics. Journal of Dairy Science 94(7):3554–3567.

Davis, C. L. and J. K. Drackley. 1998. The development, nutrition, and management of the young calf. Iowa State University Press.

Davis, H. and I. Hathaway. 1956. Comparative measurements of Holstein, Ayrshire, Guernsey, and Jersey females from birth to seven years.

Day, M. L. and G. P. Nogueira. 2013. Management of age at puberty in beef heifers to optimize efficiency of beef production. Animal Frontiers 3(4):6-11.

de Passillé, A. M. and J. Rushen. 2016. Using automated feeders to wean calves fed large amounts of milk according to their ability to eat solid feed. Journal of Dairy Science 99(5):3578-3583.

de Passillé, A. M., T. F. Borderas, and J. Rushen. 2011. Weaning age of calves fed a high milk allowance by automated feeders: effects on feed, water, and energy intake, behavioural signs of hunger, and weight gains. J Dairy Sci 94(3):1401-1408.

De Vliegher, S., L. Fox, S. Piepers, S. McDougall, and H. Barkema. 2012. Invited review: Mastitis in dairy heifers: Nature of the disease, potential impact, prevention, and control. Journal of dairy science 95(3):1025-1040.

De Vries, A. and M. Marcondes. 2020. Overview of factors affecting productive lifespan of dairy cows. Animal 14(S1):s155-s164.

Deelen, S., T. Ollivett, D. Haines, and K. Leslie. 2014. Evaluation of a Brix refractometer to estimate serum immunoglobulin G concentration in neonatal dairy calves. Journal of Dairy Science 97(6):3838-3844.

Delaby, L., J. A. Finn, G. Grange, and B. Horan. 2020. Pasture-based dairy systems in temperate lowlands: challenges and opportunities for the future. Frontiers in Sustainable Food Systems 4:278.

Dematawena, C. and P. Berger. 1997. Effect of dystocia on yield, fertility, and cow losses and an economic evaluation of dystocia scores for Holsteins. Journal of Dairy Science 80(4):754-761.

Deming, J., D. Gleeson, T. O'Dwyer, J. Kinsella, and B. O'Brien. 2018. Measuring labour input on pasture-based dairy farms using a smartphone. Journal of Dairy Science 101(10):9527-9543.

Dennis, T., F. Suarez-Mena, W. Hu, T. Hill, J. Quigley, and R. Schlotterbeck. (2019). Effects of milk replacer feeding rate and long-term antibiotic inclusion in milk replacer on performance and nutrient digestibility of Holstein dairy calves up to 4 months of age. Journal of dairy science 102(3):2094-2102.

Department of Agriculture, Food and the Marine 2020. Farm Animal Welfare Advisory Council Calf Welfare Guidelines. http://www.fawac.ie/media/fawac/content/publications/animalwelfare/Calf%20Welfare%20Guidelines%20%20FAWAC.pdf

DeVries, T. and M. Von Keyserlingk. 2009. Competition for feed affects the feeding behaviour of growing dairy heifers. Journal of dairy science 92(8):3922-3929.

Dhakal, K., C. Maltecca, J. Cassady, G. Baloche, C. Williams, and S. Washburn. 2013. Calf birth weight, gestation length, calving ease, and neonatal calf mortality in Holstein, Jersey, and crossbred cows in a pasture system. Journal of Dairy Science 96(1):690-698.

Dias, J., M. I. Marcondes, M. F. Noronha, R. T. Resende, F. S. Machado, H. C. Mantovani, K. A. Dill-McFarland, and G. Suen. 2017. Effect of pre-weaning diet on the ruminal archaeal, bacterial, and fungal communities of dairy calves. Frontiers in microbiology 8:1553.

Dillon, E., T. Hennessy, and J. Cullinan. 2015. Measuring the economic impact of improved control of sub-clinical mastitis in Irish dairy herds. The Journal of Agricultural Science 153(4):666-675.

Dillon, P. and G. Stakelum. 1989. Herbage and dosed alkanes as a grass measurement technique for dairy cows. Irish Journal of Agricultural Research 28:104.

Dillon, P., P. O'Connor, S. McCarthy, L. Shalloo, M. Linnane, D. P. Berry, F. Buckley, J. F. Mee, and B. Horan. 2006b. The effect of Holstein-Friesian genotype and feeding system on selected performance parameters of dairy cows on grass-based systems of milk production in Ireland. Teagasc.

Dillon, P., S. Crosse, G. Stakelum, and F. Flynn. 1995. The effect of calving date and stocking rate on the performance of spring-calving dairy cows. Grass and Forage Science 50(3):286-299.

Dillon, P., T. Hennessy, L. Shalloo, F. Thorne, and B. Horan. 2008. Future outlook for the Irish dairy industry: a study of international competitiveness, influence of international trade reform and requirement for change. International Journal of Dairy Technology 61(1):16-29.

Dingwell, R. T., M. M. Wallace, C. J. McLaren, C. F. Leslie, and K. E. Leslie. 2006. An evaluation of two indirect methods of estimating body weight in Holstein calves and heifers. J Dairy Sci 89.

Diskin, M. G. 2008. HeatWatch: a telemetric system for heat detection in cattle. Veterinary Quarterly 30:37-48.

Diskin, M. G. and J. M. Sreenan. 2000. Expression and detection of estrus in cattle. Reproduction Nutrition Development 40(5):481-491.

Do, C., N. Wasana, K. Cho, Y. Choi, T. Choi, B. Park, and D. Lee. 2013. The effect of age at first calving and calving interval on productive life and lifetime profit in Korean Holsteins. Asian-Australasian journal of animal sciences 26(11):1511-1517.

Dobos, R., K. Nandra, K. Riley, W. Fulkerson, A. Alford, and I. Lean. 2004. Effects of age and liveweight of dairy heifers at first calving on multiple lactation production. Australian Journal of Experimental Agriculture - AUST J EXP AGR 44.

Dobos, R., K. Nandra, K. Riley, W. Fulkerson, I. Lean, and R. Kellaway. 2001. Effects of age and liveweight at first calving on first lactation milk, protein and fat yield of Friesian heifers. Australian Journal of Experimental Agriculture 41(1):13-19.

Donworth, J. and G. Ramsbottom. 2018. Dairy Heifer Rearing Agreement.

Drackley, J. 2007. Accelerated Growth Programs for Milk-Fed Calves. Pages 87-96 in High Plains Dairy Conference. Albuquerque, NM.

Drackley, J. K. 2008. Calf nutrition from birth to breeding. Veterinary Clinics of North America: Food Animal Practice 24(1):55-86.

Drennan, M., A. Carson, and S. Crosse. 2005. Overview of animal production from pastures in Ireland. Pages 19-35 in Proc. Utilization of grazed grass in temperate animal systems: proceedings of a satellite workshop of the XXth International Grassland Congress, Cork, Ireland.

Dukes, H. H., E. A. Hewitt, and G. W. McNutt. 1935. The physiology of domestic animals. The physiology of domestic animals. (Edn. 3).

Dunn, A., A. Ashfield, B. Earley, M. Welsh, A. Gordon, and S. J. Morrison. 2017. Evaluation of factors associated with immunoglobulin G, fat, protein, and lactose concentrations in bovine colostrum and colostrum management practices in grassland-based dairy systems in Northern Ireland. Journal of Dairy Science 100(3):2068-2079.

Eastham, N. T., A. Coates, P. Cripps, H. Richardson, R. Smith, and G. Oikonomou. 2018. Associations between age at first calving and subsequent lactation performance in UK Holstein and Holstein-Friesian dairy cows. PloS one 13(6):e0197764.

Eckert, E., H. Brown, K. Leslie, T. DeVries, and M. Steele. 2015. Weaning age affects growth, feed intake, gastrointestinal development, and behaviour in Holstein calves fed an elevated plane of nutrition during the preweaning stage. Journal of dairy science 98(9):6315-6326.

Edmonson, A., I. Lean, L. Weaver, T. Farver, and G. Webster. 1989. A body condition scoring chart for Holstein dairy cows. Journal of dairy science 72(1):68-78.

Edwards, J. P., K. Mashlan, D. E. Dalley, and J. B. Pinxterhuis. 2017. A survey of dairy cow wintering practices in Canterbury, New Zealand. Animal Production Science 57(7):1323-1329.

Elsohaby, I., J. McClure, L. Waite, M. Cameron, L. Heider, and G. Keefe. 2019. Using serum and plasma samples to assess failure of transfer of passive immunity in dairy calves. Journal of dairy science 102(1):567-577.

Enevoldsen, C. and T. Kristensen. 1997. Estimation of body weight from body size measurements and body condition scores in dairy cows. Journal of dairy science 80(9):1988-1995.

Erb, H. N., R. D. Smith, P. A. Oltenacu, C. L. Guard, R. B. Hillman, P. A. Powers, M. C. Smith, and M. E. White. 1985. Path model of reproductive disorders and performance, milk fever, mastitis, milk yield, and culling in Holstein cows. J Dairy Sci 68(12):3337-3349.

Erickson, P. S. and K. F. Kalscheur. 2020. Nutrition and feeding of dairy cattle. Animal Agriculture: 157-180.

Erickson, P. S., D. Schauff, and M. R. Murphy. 1989. Diet digestibility and growth of Holstein calves fed acidified milk replacers containing soy protein concentrate. Journal of dairy science 72(6):1528-1533.

Esslemont, R., M. Kossaibati, and J. Allcock. 2001. Economics of fertility in dairy cows. BSAP Occasional Publication 26(1):19-29.

Ettema, J. and J. Santos. 2004. Impact of age at calving on lactation, reproduction, health, and income in first-parity Holsteins on commercial farms. Journal of dairy science 87(8):2730-2742.

Evans, R., F. Buckley, P. Dillon, and R. Veerkamp. 2002. Genetic parameters for production and fertility in spring-calving Irish dairy cattle. Irish Journal of Agricultural and Food Research: 43-54.

Evans, R. D., M. Wallace, D. J. Garrick, P. Dillon, D. P. Berry, and V. Olori. 2006. Effects of calving age, breed fraction and month of calving on calving interval and survival across parities in Irish spring-calving dairy cows. Livestock Science 100(2):216-230.

Evers, S., S. McParland, L. Delaby, K. Pierce, and B. Horan. 2021. Analysis of milk solids production and mid-lactation bodyweight to evaluate cow production efficiency on commercial dairy farms. Livestock Science: 104691.

Faber, S., N. Faber, T. McCauley, and R. Ax. 2005. Case Study: Effects of Colostrum Ingestion on Lactational Performance 1. The Professional Animal Scientist 21(5):420-425.

Ferrell, C. 1982. Effects of post weaning rate of gain on onset of puberty and productive performance of heifers of different breeds. Journal of Animal Science 55(6):1272-1283.

Ferret, A., J. Plaixats, G. Caja, J. Gasa, and P. Prio. 1999. Using markers to estimate apparent dry matter digestibility, faecal output and dry matter intake in dairy ewes fed Italian ryegrass hay or alfalfa hay. Small Ruminant Research 33(2):145-152.

Finneran, E., P. Crosson, P. O'Kiely, L. Shalloo, D. Forristal, and M. Wallace. 2010. Simulation modelling of the cost of producing and utilizing feeds for ruminants on Irish farms. Journal of Farm Management 14(2):95-116.

Finneran, E., P. Crosson, P. O'Kiely, L. Shalloo, P. Forristal, and M. Wallace. 2012. Economic modelling of an integrated grazed and conserved perennial ryegrass forage production system. Grass and Forage Science 67(2):162-176.

Fischer-Tlustos, A., K. Hertogs, J. Van Niekerk, M. Nagorske, D. Haines, and M. Steele. 2020. Oligosaccharide concentrations in colostrum, transition milk, and mature milk of primi-and multiparous Holstein cows during the first week of lactation. Journal of dairy science 103(4):3683-3695.

Foley, J. and D. Otterby. 1978. Availability, storage, treatment, composition, and feeding value of surplus colostrum: a review. Journal of Dairy Science 61(8):1033-1060.

Ford Jr, J. and C. Park. 2001. Nutritionally directed compensatory growth enhances heifer development and lactation potential. Journal of Dairy Science 84(7):1669-1678.

Freer, M., H. Dove, and J. V. Nolan. 2007. Nutrient requirements of domesticated ruminants. CSIRO Publishing, Collingwood.

French, P., E. O'Riordan, A. Moloney, P. O'Kiely, and P. Caffrey. 2001. Effects of concentrate level and grazing system on the performance of beef cattle grazing autumn herbage. Irish Journal of Agricultural and Food Research: 33-44.

Froidmont, E., P. Mayeres, P. Picron, A. Turlot, V. Planchon, and D. Stilmant. 2013. Association between age at first calving, year and season of first calving and milk production in Holstein cows. Animal 7(4):665-672.

Fulkerson, W. J., K. McKean, K. S. Nandra, and I. M. Barchia. 2005. Benefits of accurately allocating feed on a daily basis to dairy cows grazing pasture. Australian Journal of Experimental Agriculture 45(4):331-336.

Gaafar, H. M. A., S. M. Shamiah, M. A. A. El-Hamd, A. A. Shitta, and M. A. T. El-Din. 2011. Dystocia in Friesian cows and its effects on postpartum reproductive performance and milk production. Tropical Animal Health and Production 43(1):229-234.

Gabler, M. T., P. R. Tozer, and A. J. Heinrichs. 2000. Development of a Cost Analysis Spreadsheet for Calculating the Costs to Raise a Replacement Dairy Heifer. Journal of Dairy Science 83(5):1104–1109.

Ganche, E., L. Delaby, M. O'Donovan, T. Boland, N. Galvin, and E. Kennedy. 2013. Post-grazing sward height imposed during the first 10 weeks of lactation: Influence on early and total lactation dairy cow production, and spring and annual sward characteristics. Livestock Science 157(1):299-311.

Gardner, R., J. Schuh, and L. Vargus. 1977. Accelerated growth and early breeding of Holstein heifers. Journal of dairy science 60(12):1941-1948.

Garrett, W. 1979. Relationships among Diet, Metabolizable Energy Utilization and Net Energy Values of Feedstuffs. Journal of animal science 49(5):1403-1409.

Gavin, K., H. Neibergs, A. Hoffman, J. N. Kiser, M. A. Cornmesser, S. A. Haredasht, B. Martínez-López, J. R. Wenz, and D. A. Moore. 2018. Low colostrum yield in Jersey cattle and potential risk factors. Journal of Dairy Science 101(7):6388-6398.

Geary, U., N. Lopez-Villalobos, N. Begley, F. McCoy, B. O'Brien, L. O'Grady, and L. Shalloo. 2012. Estimating the effect of mastitis on the profitability of Irish dairy farms. Journal of Dairy Science 95(7):3662-3673.

Gill, G. and F. Allaire. 1976. Relationship of age at first calving, days open, days dry, and herd life to a profit function for dairy cattle. Journal of Dairy Science 59(6):1131-1139.

Goddard, M. and C. Grainger. 2004. A review of the effects of dairy breed on feed conversion efficiency-an opportunity lost? Science Access 1(1):77-80.

Godden, S. M., J. P. Fetrow, J. M. Feirtag, L. R. Green, and S. J. Wells. 2005. Economic analysis of feeding pasteurized nonsaleable milk versus conventional milk replacer to dairy calves. Journal of the American Veterinary Medical Association 226(9):1547-1554.

Godden, S. 2008. Colostrum Management for Dairy Calves. Veterinary Clinics of North America: Food Animal Practice 24(1):19-39.

Godden, S. M., J. E. Lombard, and A. R. Woolums. 2019. Colostrum Management for Dairy Calves. Veterinary Clinics: Food Animal Practice 35(3):535-556.

González, L., I. Kyriazakis, and L. Tedeschi. 2018. Precision nutrition of ruminants: approaches, challenges and potential gains. Animal 12(s2):s246-s261.

Gorrill, A. 1964a. Pasture rearing and milk-replacer feeding of dairy calves. Canadian Journal of Animal Science 44(2):235-247.

Gorrill, A. 1964b. A comparison of weaning dairy calves by body weight versus age from whole milk or milk-replacer. Canadian Journal of Animal Science 44(3):327-333.

Govil, K., D. Yadav, A. Patil, S. Nayak, R. Baghel, P. Yadav, C. Malapure, and D. Thakur. 2017. Feeding management for early rumen development in calves. J. Entomol. Zool. Stud 5(3):1132-1139.

Gregorini, P., C. Clark, J. Jago, C. Glassey, K. McLeod, and A. Romera. 2009. Restricting time at pasture: Effects on dairy cow herbage intake, foraging behaviour, hunger-related hormones, and metabolite concentration during the first grazing session. Journal of Dairy Science 92(9):4572-4580.

Grummer, R. R. 1995. Impact of changes in organic nutrient metabolism on feeding the transition dairy cow. Journal of animal science 73(9):2820-2833.

Grummer, R. R., D. G. Mashek, and A. Hayirli. 2004. Dry matter intake and energy balance in the transition period. Veterinary Clinics: Food Animal Practice 20(3):447-470.

Guy, M., T. McFadden, D. Cockrell, and T. Besser. 1994. Regulation of colostrum formation in beef and dairy cows. Journal of dairy science 77(10):3002-3007.

Haisan, J., M. Oba, D. J. Ambrose, and M. A. Steele. 2018. Short communication: The effects of offering a high or low plane of milk preweaning on insulin-like growth factor and insulin-like growth factor binding proteins in dairy heifer calves. Journal of Dairy Science 101(12):11441-11446.

Halachmi, I., Y. Edan, E. Maltz, U. Peiper, U. Moallem, and I. Brukental. 1998. A real-time control system for individual dairy cow food intake. Computers and Electronics in Agriculture 20(2):131-144.

Hamann, J. and V. Krömker. 1997. Potential of specific milk composition variables for cow health management. Livestock Production Science 48(3):201-208.

Handcock, R., T. Lopdell, and L. McNaughton. 2016. More dairy heifers are achieving liveweight targets. New Zealand Society of Animal Production 2016. Accessed on 7 September 2001. https://www.nzsap.org/system/files/proceedings/%2326%20Rhiannon%20Handcock.pdf.

Handcock, R., N. Lopez-Villalobos, L. McNaughton, G. Edwards, and R. Hickson. 2018. Positive relationship between live weight at first calving and first lactation milk production. Page 126 in Proc. Proceedings of the World Congress on Genetics Applied to Livestock Production.

Handcock, R. C., Lopez-Villalobos, N., McNaughton, L. R., Back, P. J., Edwards, G. R., & Hickson, R. E. 2019a. Live weight and growth of Holstein-Friesian, Jersey and crossbred dairy heifers in New Zealand. New Zealand Journal of agricultural research, 62(2), 173-183.

Handcock, R., N. Lopez-Villalobos, L. McNaughton, P. Back, G. Edwards, and R. Hickson. 2019b. Stayability of dairy heifers as affected by live weight and growth prior to first calving. Live weight and growth of dairy heifers are important for subsequent milk production and reproductive performance: 123.

Handcock, R., N. Lopez-Villalobos, L. McNaughton, P. Back, G. Edwards, and R. Hickson. 2019c. Positive relationships between body weight of dairy heifers and their first-lactation and accumulated three-parity lactation production. Journal of dairy science 102(5):4577-4589.

Handcock, R. C., N. Lopez-Villalobos, L. R. McNaughton, P. J. Back, G. R. Edwards, and R. E. Hickson. 2020. Body weight of dairy heifers is positively associated with reproduction and stayability. Journal of Dairy Science 103(5):4466-4474.

Handcock, R. C., C. M. Jenkinson, R. Laven, L. R. McNaughton, N. Lopez-Villalobos, P. J. Back and R. E. Hickson. 2021. Linear versus seasonal growth of dairy heifers decreased age at puberty but did not affect first lactation milk production. New Zealand Journal of Agricultural Research 64(1):83-100.

Hanks, J. and M. Kossaibati. 2018. Key Performance Indicators for the UK national dairy herd. A study of herd performance in 500:1-26.

Hanrahan, L., A. Geoghegan, M. O'Donovan, V. Griffith, E. Ruelle, M. Wallace, and L. Shalloo. 2017. PastureBase Ireland: A grassland decision support system and national database. Computers and Electronics in Agriculture 136:193-201.

Hare, E., H. D. Norman, and J. R. Wright. 2006. Trends in Calving Ages and Calving Intervals for Dairy Cattle Breeds in the United States. Journal of Dairy Science 89(1):365-370.

Hawkins, A., K. Burdine, D. Amaral-Phillips, and J. H. C. Costa. 2019. An Economic Analysis of the Costs Associated with Pre-Weaning Management Strategies for Dairy Heifers. Animals 9(7):471.

Hawkins, A., K. H. Burdine, D. M. Amaral-Phillips, and J. H. C. Costa. 2020. Effects of Housing System on Dairy Heifer Replacement Cost From Birth to Calving: Evaluating Costs of Confinement, Dry-Lot, and Pasture-Based Systems and Their Impact on Total Rearing Investment. Front Vet Sci 7(625).

Hayes, C. J., C. G. McAloon, C. I. Carty, E. G. Ryan, J. F. Mee, and L. O'Grady. 2019. The effect of growth rate on reproductive outcomes in replacement dairy heifers in seasonally calving, pasture-based systems. Journal of dairy science 102(6):5599-5611.

Heinrichs, A., G. Rogers, and J. Cooper. 1992. Predicting body weight and wither height in Holstein heifers using body measurements. Journal of dairy science 75(12):3576-3581.

Heinrichs, A. J. 1993. Raising dairy replacements to meet the needs of the 21st century. Journal of dairy science 76(10):3179-3187.

Heinrichs, A. J. 1996. Nutrition and management of replacement cattle. Animal Feed Science and Technology 59(1):155-166.

Heinrichs, J., C. Jones, and K. Bailey. 1997. Milk components: Understanding the causes and importance of milk fat and protein variation in your dairy herd. Dairy Anim. Sci 5:1e-8e.

Heinrichs, A. J., B. S. Heinrichs, O. Harel, G. W. Rogers, and N. T. Place. 2005. A Prospective Study of Calf Factors Affecting Age, Body Size, and Body Condition Score at First Calving of Holstein Dairy Heifers. Journal of Dairy Science 88(8):2828-2835.

Heinrichs, A. J. and B. S. Heinrichs. 2011. A prospective study of calf factors affecting first-lactation and lifetime milk production and age of cows when removed from the herd1. Journal of Dairy Science 94(1):336-341.

Hengst, B., L. Nemec, R. Rastani, and T. Gressley. 2012. Effect of conventional and intensified milk replacer feeding programs on performance, vaccination response, and neutrophil mRNA levels of Holstein calves. Journal of dairy science 95(9):5182-5193.

Hennessy, D., M. O’Donovan, P. French, and A. Laidlaw. 2008. Factors influencing tissue turnover during winter in perennial ryegrass-dominated swards. Grass and Forage Science 63(2):202-211.

Hennessy, D., L. Delaby, A. van den Pol-van Dasselaar, and L. Shalloo. 2020. Increasing grazing in dairy cow milk production systems in Europe. Sustainability 12(6):2443.

Hepola, H. 2008. Rearing strategies of young dairy calves in relation to production, behaviour and welfare. https://helda.helsinki.fi/bitstream/handle/10138/20754/rearing.pdf?sequence=2

Herlihy, M. M., D. P. Berry, M. A. Crowe, M. G. Diskin, and S. T. Butler. 2011. Evaluation of protocols to synchronize estrus and ovulation in seasonal calving pasture-based dairy production systems. Journal of Dairy Science 94(9):4488-4501.

Herlihy, M., M. Crowe, D. Berry, M. Diskin, and S. Butler. 2013. Factors associated with fertility outcomes in cows treated with protocols to synchronize estrus and ovulation in seasonal-calving, pasture-based dairy production systems. Journal of dairy science 96(3):1485-1498.

Hill, T. M., H. G. Bateman, J. M. Aldrich, and R. L. Schlotterbeck. 2008. Effects of the Amount of Chopped Hay or Cottonseed Hulls in a Textured Calf Starter on Young Calf Performance. Journal of Dairy Science 91(7):2684-2693.

Hill, T., H. Bateman II, J. Aldrich, and R. Schlotterbeck. 2009. Effect of consistency of nutrient intake from milk and milk replacer on dairy calf performance. The Professional Animal Scientist 25(1):85-92.

Hoffman, P. and D. A. Funk. 1992. Applied Dynamics of Dairy Replacement Growth and Management1. Journal of Dairy Science 75(9):2504-2516.

Hoffman, P. 1997. Optimum body size of Holstein replacement heifers. Journal of Animal Science 75(3):836-845.

Hoffman, P., K. Weigel, and R. Wernberg. 2008a. Evaluation of equations to predict dry matter intake of dairy heifers. Journal of dairy science 91(9):3699-3709.

Hoffman, P. C., K. A. Weigel, and R. M. Wernberg. 2008b. Evaluation of Equations to Predict Dry Matter Intake of Dairy Heifers. Journal of Dairy Science 91(9):3699-3709.

Hoffman, P. and K. Kester. 2013. Estimating dry matter intake of dairy heifers. Forage Focus December. Accessed on 7 September 2021. http://www.midwestforage.org/pdf/819.pdf.pdf

Hopkins, B. and J. Quigley III. 1997. Effects of method of colostrum feeding and colostrum supplementation on concentrations of immunoglobulin G in the serum of neonatal calves. Journal of dairy science 80(5):979-983.

Horan, B., J. Mee, M. Rath, P. O'connor, and P. Dillon. 2004. The effect of strain of Holstein-Friesian cow and feeding system on reproductive performance in seasonal-calving milk production systems. Animal Science 79(3):453-467.

Horan, B., J. F. Mee, P. O’Connor, M. Rath, and P. Dillon. 2005. The effect of strain of Holstein-Friesian cow and feeding system on postpartum ovarian function, animal production and conception rate to first service. Theriogenology 63(3):950-971.

Horan, B., P. Faverdin, L. Delaby, M. Rath, and P. Dillon. 2006. The effect of strain of Holstein-Friesian dairy cow and pasture-based system on grass intake and milk production. Animal Science 82(4):435-444.

Hudson, G. and L. D. Van Vleck. 1981. Relationship between production and stayability in Holstein cattle. Journal of Dairy Science 64(11):2246-2250.

Humphreys, J., I. Casey, and A. Laidlaw. 2009. Comparison of milk production from clover-based and fertilizer-N-based grassland on a clay-loam soil under moist temperate climatic conditions. Irish Journal of Agricultural and Food Research: 189-207.

Hutchison, J., P. VanRaden, D. Null, J. Cole, and D. Bickhart. 2017. Genomic evaluation of age at first calving. Journal of Dairy Science 100(8):6853-6861.

ICBF. 2018. HerdPlus Dairy Calving Statistics. Accessed on 12 September 2021. https://www.icbf.com/wp-content/uploads/2018/09/Dairy-Calving-Stats-2018-1.pdf.

ICBF. 2019. What is the Optimum Age at First Calving in Dairy Heifers? Accessed 10 September 2021. https://www.icbf.com/wp-content/uploads/2019/11/Optimum-age-at-first-calving.pdf

ICBF. 2020a. Dairy Calving Statistics 2020. Accessed on 12 September 2021. https://www.icbf.com/wp-content/uploads/2020/10/Dairy-Calving-Statistics-pdf-02.10.20.pdf

ICBF. 2020b. Number of recorded Dairy Inseminations recorded on Dairy Cows Jan - Jun 2019, Jan - Jun 2020. https://www.icbf.com/?p=16056.

INRA. 2010. Alimentation des bovins, ovins et caprins, Quae ed. p. 311.

James, B. and C. Scott. 2016. Using the Calf Milk Pasteurization Evaluator Spreadsheet. https://www.extension.iastate.edu/dairyteam/files/page/files/Copy%20of%20pasteurizer%20evaluator%20tool-penn%20state.xls

Jasper, J. and D. M. Weary. 2002. Effects of Ad Libitum Milk Intake on Dairy Calves. Journal of Dairy Science 85(11):3054-3058.

Jaster, E. 2005. Evaluation of quality, quantity, and timing of colostrum feeding on immunoglobulin G1 absorption in Jersey calves. Journal of dairy science 88(1):296-302.

Johnson, P., K. Olson, R. Gates, H. Patterson, M. Hubert, D. Landblom, J. Kincheloe, H. Richter, and A. Grove. 2015. Early Weaning Reduces Rangeland Herbage Disappearance. Crop, Forage and Turfgrass Management 1.

Johnson, K., N. Chancellor, C. Burn, and D. Wathes. 2017. Analysis of pre-weaning feeding policies and other risk factors influencing growth rates in calves on 11 commercial dairy farms. Animal: 1-11.

Kavanagh, S. 2016. Feeding the Dairy Cow. Teagasc Dairy Manual. Accessed on 7 September 2021. https://www.teagasc.ie/media/website/publications/2016/Dairy-Manual-Section6.pdf.

Keady, T., C. Mayne, D. Kilpatrick, and M. McCoy. 2005. Effect of level and source of nutrients in late gestation on subsequent milk yield and composition and fertility of dairy cows. Livestock Production Science 94(3):237-248.

Kehoe, S., C. Dechow, and A. Heinrichs. 2007. Effects of weaning age and milk feeding frequency on dairy calf growth, health and rumen parameters. Livestock Science 110(3):267-272.

Kennedy, E., M. O'Donovan, J. Murphy, F. O'Mara, and L. Delaby. 2006. The effect of initial spring grazing date and subsequent stocking rate on the grazing management, grass dry matter intake and milk production of dairy cows in summer. Grass and Forage Science 61(4):375-384.

Kennedy, E., M. O’Donovan, J. Murphy, L. Delaby, and F. O’Meara. 2007. Effect of spring grazing date and stocking rate on sward characteristics and dairy cow production during midlactation. Journal of Dairy Science 90(4):2035-2046.

Kennedy, E., M. O'Donovan, L. Delaby, and F. P. O'Mara. 2008. Effect of herbage allowance and concentrate supplementation on dry matter intake, milk production and energy balance of early lactating dairy cows. Livestock Science 117(2):275-286.

Kennedy, E., M. McEvoy, J. Murphy, and M. O’Donovan. 2009. Effect of restricted access time to pasture on dairy cow milk production, grazing behaviour, and dry matter intake. Journal of Dairy Science 92(1):168-176.

Kennedy, E., J. Curran, B. Mayes, M. McEvoy, J. Murphy, and M. O'Donovan. 2011. Restricting dairy cow access time to pasture in early lactation: the effects on milk production, grazing behaviour and dry matter intake. Animal 5(11):1805-1813.

Kennedy, E., L. Shalloo, F. Buckley, and S. Butler. 2012. Replacement heifer management. Proc. Dairy Cow Fertility Reproductive performance for efficient pasture-based systems.

Kennedy, E., J. P. Murphy, F. Coughlan, and S. Fitzgerald. 2013. Effects of diet during the first winter on replacement heifer weight gain and body condition score during the subsequent grazing season. Pages 553-554 in Proc. The XXII International Grassland Congress: Revitalizing Grasslands to Sustain Our Communities, Sydney, Australia.

Kennedy, E. a. M., J.P. 2017. Replacement heifers: Achieving target weight. Moorepark 2017 Irish dairying- resilient technologies: 156-157.

Kennedy, J., P. Dillon, L. Delaby, P. Faverdin, G. Stakelum, and M. Rath. 2003. Effect of genetic merit and concentrate supplementation on grass intake and milk production with Holstein Friesian dairy cows. Journal of dairy science 86(2):610-621.

Keogh, B., P. French, T. McGrath, T. Storey, and F. Mulligan. 2009. Comparison of the performance of dairy cows offered kale, swedes and perennial ryegrass herbage in situ and perennial ryegrass silage fed indoors in late pregnancy during winter in Ireland. Grass and forage science 64(1):49-56.

Kertz, A., B. Barton, and L. F. Reutzel. 1998. Relative Efficiencies of Wither Height and Body Weight Increase from Birth until First Calving in Holstein Cattle. Journal of dairy science 81:1479-1482.

Kertz, A., L. Prewitt, and J. Everett. 1979. An early weaning calf program: summarization and review. Journal of Dairy Science 62(11):1835-1843.

Kertz, A., L. Reutzel, and J. Mahoney. 1984. Ad libitum water intake by neonatal calves and its relationship to calf starter intake, weight gain, faeces score, and season. Journal of Dairy Science 67(12):2964-2969.

Khan, A., A. Bach, D. Weary, and M. Keyserlingk. 2015. Invited review: Transitioning from milk to solid feed in dairy heifers. Journal of Dairy Science 99:885–902.

Khan, M. A., D. M. Weary, D. M. Veira, and M. A. G. von Keyserlingk. 2012. Post weaning performance of heifers fed starter with and without hay during the milk-feeding period. Journal of Dairy Science 95(7):3970-3976.

Khan, M. A., H. J. Lee, W. S. Lee, H. S. Kim, S. B. Kim, K. S. Ki, J. K. Ha, H. G. Lee, and Y. J. Choi. 2007. Pre- and post-weaning performance of Holstein female calves fed milk through step-down and conventional methods. J Dairy Sci 90(2):876-885.

Khan, M. A., H. J. Lee, W. S. Lee, H. S. Kim, S. B. Kim, S. B. Park, K. S. Baek, J. K. Ha, and Y. J. Choi. 2008. Starch Source Evaluation in Calf Starter: II. Ruminal

Parameters, Rumen Development, Nutrient Digestibilities, and Nitrogen Utilization in Holstein Calves. Journal of Dairy Science 91(3):1140-1149.

Khan, M., D. Weary, and M. Von Keyserlingk. 2011. Invited review: Effects of milk ration on solid feed intake, weaning, and performance in dairy heifers. Journal of Dairy Science 94(3):1071-1081.

Kim, I. H. and J. K. Jeong. 2019. Risk factors limiting first service conception rate in dairy cows and their economic impact. Asian-Australasian journal of animal sciences 32(4):519-526.

Klaus, G., A. Bennett, and E. Jones. 1969. A quantitative study of the transfer of colostral immunoglobulins to the newborn calf. Immunology 16(3):293.

Kok, A., C. van Middelaar, B. Engel, A. van Knegsel, H. Hogeveen, B. Kemp, and I. de Boer. 2016. Effective lactation yield: A measure to compare milk yield between cows with different dry period lengths. Journal of dairy science 99(4):2956-2966.

Kuhi, H. D., N. G. Hossein-Zadeh, S. López, S. Falahi, and J. France. 2019. Sinusoidal function to describe the growth curve of dairy heifers. Animal Production Science 59(6):1039-1047.

Kull, E., A. Sahin, S. Atasever, E. Ugurlutepe, and M. Soydaner. 2019. The effects of somatic cell count on milk yield and milk composition in Holstein cows.

Lahart, B., S. McParland, E. Kennedy, T. M. Boland, T. Condon, M. Williams, N. Galvin, B. McCarthy, and F. Buckley. 2019. Predicting the dry matter intake of grazing dairy cows using infrared reflectance spectroscopy analysis. Journal of Dairy Science 102(10):8907-8918.

Lammers, B., A. Heinrichs, and R. Kensinger. 1999. The effects of accelerated growth rates and oestrogen implants in prepubertal Holstein heifers on growth, feed efficiency, and blood parameters. Journal of dairy science 82(8):1746-1752.

Lane, E. A., M. A. Crowe, M. E. Beltman, and S. J. More. 2013. The influence of cow and management factors on reproductive performance of Irish seasonal calving dairy cows. Animal reproduction science 141(1-2):34-41.

Läpple, D., T. Hennessy, and M. O'Donovan. 2012. Extended grazing: A detailed analysis of Irish dairy farms. Journal of Dairy Science 95(1):188-195.

Larson, B., H. Heary, and J. Devery. 1980. Immunoglobulin production and transport by the mammary gland. Journal of Dairy Science 63(4):665-671.

Lasdon, L., R. Fox, and M. Ratner. 1973. Nonlinear Optimization Using the Generalized Reduced Gradient Method. Revue Française d'Automatique, Informatique, Recherche Opérationnelle. Série Verte 8:63.

Le Cozler, Y., V. Lollivier, P. Lacasse, and C. Disenhaus. 2008. Rearing strategy and optimizing first-calving targets in dairy heifers: a review. Animal 2(9):1393-1404.

Le Cozler, Y., J. R. Peccatte, and L. Delaby. 2010. A comparative study of three growth profiles during rearing in dairy heifers: Effect of feeding intensity during two successive winters on performances and longevity. Livestock Science 127(2):238-247.

Le Cozler, Y., C. Allain, A. Caillot, J. M. Delouard, L. Delattre, T. Luginbuhl, and P. Faverdin. 2019. High-precision scanning system for complete 3D cow body shape imaging and analysis of morphological traits. Computers and Electronics in Agriculture 157:447-453

Leaver, J. 1973. Rearing of dairy cattle. 4. Effect of concentrate supplementation on the live-weight gain and feed intake of calves offered roughages ad libitum. Animal Science 17(1):43-52.

Lee, J.Y., and I.H. Kim. 2006. Advancing parity is associated with high milk production at the cost of body condition and increased periparturient disorders in dairy herds. J Vet Sci 7(2):161-166.

Lembeye, F., N. López-Villalobos, J. Burke, S. Davis, J. Richardson, N. Sneddon, and D. Donaghy. 2016. Comparative performance in Holstein-Friesian, Jersey and crossbred cows milked once daily under a pasture-based system in New Zealand. New Zealand Journal of Agricultural Research 59(4):351-362.

Lesmeister, J., P. J. Burfening, and R. Blackwell. 1973. Date of first calving in beef cows and subsequent calf production. Journal of Animal Science 36(1):1-6.

Litherland, A., S. Woodward, D. Stevens, D. McDougal, C. Boom, T. Knight, and M. Lambert. 2002. Seasonal variations in pasture quality on New Zealand sheep and beef farms. Pages 138-142 in Proc. Proceedings-New Zealand society of animal production. New Zealand Society of Animal Production; 1999.

Little, W. and R. Kay. 1979. The effects of rapid rearing and early calving on the subsequent performance of dairy heifers. Animal Science 29(1):131-142.

Lohakare, J., K.-H. Südekum and A. Pattanaik. 2012. Nutrition-induced changes of growth from birth to first calving and its impact on mammary development and first-lactation milk yield in dairy heifers: a review. Asian-Australasian journal of animal sciences 25(9):1338.

Lorenz, I., J. F. Mee, B. Earley, and S. J. More. 2011. Calf health from birth to weaning. I. General aspects of disease prevention. Irish veterinary journal 64(1):1-8.

Lukuyu, M. N., J. P. Gibson, D. B. Savage, A. J. Duncan, F. D. N. Mujibi, and A. M. Okeyo. 2016. Use of body linear measurements to estimate liveweight of crossbred dairy cattle in smallholder farms in Kenya. SpringerPlus 5(1):63.

Macdonald, K., C. Glassey, J. Kay, and C. Wims. 2018. Effect of post-grazing residual pasture height in spring on pasture quality in summer and autumn. Sustainable meat and milk production from grasslands: 277.

Macdonald, K., J. Penno, A. Bryant, and J. Roche. 2005. Effect of feeding level pre-and post-puberty and body weight at first calving on growth, milk production, and fertility in grazing dairy cows. Journal of Dairy Science 88(9):3363-3375.

MacFarlane, J., D. Grove-White, M. Royal, and R. Smith. 2014. Use of plasma samples to assess passive transfer in calves using refractometry: comparison with serum and clinical cut-off point. Veterinary Record 174(12):303-303.

MacMillan, J. 2012. Developing a breeding program for compact calving. Dairy Cow Fertility: 72.

MacPherson, J., H. Berends, L. Leal, J. Cant, J. Martín-Tereso, and M. Steele. 2016. Effect of plane of milk replacer intake and age on glucose and insulin kinetics and abomasal emptying in female Holstein Friesian dairy calves fed twice daily. Journal of dairy science 99(10):8007-8017.

Maher, J., G. Stakelum, and M. Rath. 2003. Effect of daily herbage allowance on the performance of spring-calving dairy cows. Irish Journal of Agricultural and food research: 229-241.

Malmuthuge, N. and L. L. Guan. 2017. Understanding the gut microbiome of dairy calves: Opportunities to improve early-life gut health1. Journal of Dairy Science 100(7):5996-6005.

Margerison, J. and N. Downey. 2005. Guidelines for optimal dairy heifer rearing and herd performance. Calf and heifer rearing: principles of rearing the modern dairy heifer from calf to calving. 60th University of Nottingham Easter School in Agricultural Science, Nottingham, UK. 23rd-24th March 2004:307-338.

Marquez, D., M. Paulino, L. Rennó, F. Villadiego, R. Ortega, D. Moreno, L. Martins, D. De Almeida, M. Gionbelli, and M. Manso. 2017. Supplementation of grazing beef cows during gestation as a strategy to improve skeletal muscle development of the offspring. Animal 11(12):2184-2192.

Martín, N. P., R. E. Hickson, R. P. de Clifford, W. Tulley, N. Lopez-Villalobos, and P. J. Back. 2020. Production benefits from meeting liveweight targets in dairy heifers. New Zealand Journal of Agricultural Research 63(2):220-232.

Mayasari, N., G. de Vries Reilingh, M. Nieuwland, G. Remmelink, H. Parmentier, B. Kemp, and A. Van Knegsel. 2015. Effect of maternal dry period length on colostrum immunoglobulin content and on natural and specific antibody titres in calves. Journal of Dairy Science 98(6):3969-3979.

Mayes, R., C. Lamb, and P. M. Colgrove. 1986. The use of dosed and herbage n-alkanes as markers for the determination of herbage intake. The Journal of Agricultural Science 107(1):161-170.

Maynou, G., A. Bach, and M. Terré. 2017. The feeding of waste milk to Holstein calves affects antimicrobial resistance of Escherichia coli and Pasteurella multocida isolated from fecal and nasal swabs. Journal of dairy science 100(4):2682-2694.

McAloon, C. G., Á. Macken-Walsh, L. Moran, P. Whyte, S. J. More, L. O'Grady, and M. L. Doherty. 2017. Johnes disease in the eyes of Irish cattle farmers: a qualitative narrative research approach to understanding implications for disease management. Preventive veterinary medicine 141:7-13.

McCarthy, B., M. Dineen, C. Guy, F. Coughlan, and T. Gilliland. 2015. The effect of tetraploid and diploid perennial ryegrass swards sown with and without clover on milk and herbage production. Grassland Science in Europe 20:259-261.

McCarthy, S., B. Horan, M. Rath, M. Linnane, P. O'Connor, and P. Dillon. 2007. The influence of strain of Holstein-Friesian dairy cow and pasture-based feeding system on grazing behaviour, intake and milk production. Grass and Forage Science 62(1):13-26.

McDougall, S. 2006. Reproduction performance and management of dairy cattle. Journal of Reproduction and Development 52(1):185-194.

McEvoy, M., E. Kennedy, J. Murphy, T. Boland, L. Delaby, and M. O'Donovan. 2008. The effect of herbage allowance and concentrate supplementation on milk production performance and dry matter intake of spring-calving dairy cows in early lactation. Journal of Dairy Science 91(3):1258-1269.

McEvoy, M., M. O'Donovan, E. Kennedy, J. Murphy, L. Delaby, and T. Boland. 2009. Effect of pre-grazing herbage mass and pasture allowance on the lactation performance of Holstein-Friesian dairy cows. Journal of Dairy Science 92(1):414-422.

McGee, M. 2015. Feed efficiency in beef finishing systems. Irish Grassland Association. J. 49:97-105.

McGovern, F., B. Garry, P. Creighton, N. Galvin, D. Hennessy, E. Kennedy, N. McHugh, M. O'Donovan, and M. Beecher. 2021. Validating the n-alkane technique for determining herbage dry matter intake in sheep offered perennial ryegrass harvested at varying growth stages and seasons. Animal Feed Science and Technology 279:115025.

McGuirk, B., R. Forsyth, and H. Dobson. 2007. Economic cost of difficult calvings in the United Kingdom dairy herd. Veterinary Record 161(20):685-687.

McGuirk, S. M. and M. Collins. 2004. Managing the production, storage, and delivery of colostrum. Veterinary Clinics of North America: Food Animal Practice 20(3):593-603.

McHugh, N., J. Kearney, and D. Berry. 2011. The effect of dystocia on subsequent performance in dairy cows. Moorepark Res Rep 2011:15.

McKay, Z. C., M. B. Lynch, F. J. Mulligan, G. Rajauria, C. Miller, and K. M. Pierce. 2019. The effect of concentrate supplementation type on milk production, dry matter intake, rumen fermentation, and nitrogen excretion in late-lactation, Spring-calving grazing dairy cows. Journal of Dairy Science 102(6):5042-5053.

McLean, D. and M. Freeman. 1996. Benefits from better-grown heifers. Pages 72-74 in Proc. Proceedings-Australian society of animal production. Australian society of animal production.

McNamara, S., F. P. O'Mara, M. Rath, and J. J. Murphy. 2003. Effects of Different Transition Diets on Dry Matter Intake, Milk Production, and Milk Composition in Dairy Cows. Journal of Dairy Science 86(7):2397-2408.

McNaughton, L. R., K. M. Sanders, J. E. Pryce, G. E. Bracefield, S. J. Harcourt, and R. J. Spelman. 2007. Phenotypic relationships between the interval from calving to first luteal activity and fertility in a seasonal dairy production system. Animal Reproduction Science 102(1):98-110.

McNaughton, L. and T. Lopdell. 2012. Brief Communication: Are dairy heifers achieving live weight targets? Pages 120-122 in Proc. Proceedings of the New Zealand Society of Animal Production. Accessed on 7 September 2021. http://www.nzsap.org/system/files/proceedings/2012/ab12026.pdf

McNaughton, L., & Lopdell, T. 2013. Effect of heifer live weight on calving pattern and milk production. Proceedings of the New Zealand Society of Animal Production. Accessed on 7 September 2021. http://www.nzsap.org/system/files/proceedings/ab13026.pdf

Meale, S., L. Leal, J. Martín-Tereso, and M. Steele. 2015. Delayed weaning of Holstein bull calves fed an elevated plane of nutrition impacts feed intake, growth and potential markers of gastrointestinal development. Animal Feed Science and Technology 209:268-273.

Mee, J. F. 2008a. Newborn Dairy Calf Management. Veterinary Clinics of North America: Food Animal Practice 24(1):1-17.

Mee, J. F. 2008b. Prevalence and risk factors for dystocia in dairy cattle: A review. The Veterinary Journal 176(1):93-101.

Mee, J. F., D. P. Berry, and A. R. Cromie. 2011. Risk factors for calving assistance and dystocia in pasture-based Holstein–Friesian heifers and cows in Ireland. The Veterinary Journal 187(2):189-194.

Miller-Cushon, E. K., R. Bergeron, K. E. Leslie, and T. J. DeVries. 2013. Effect of milk feeding level on development of feeding behaviour in dairy calves. Journal of Dairy Science 96(1):551-564.

Moallem, U., D. Werner, H. Lehrer, M. Zachut, L. Livshitz, S. Yakoby, and A. Shamay. 2010. Long-term effects of ad libitum whole milk prior to weaning and prepubertal protein supplementation on skeletal growth rate and first-lactation milk production. Journal of Dairy Science 93(6):2639-2650.

Moallem, U., D. Werner, H. Lehrer, M. Zachut, L. Livshitz, S. Yakoby, and A. Shamay. 2010. Long-term effects of ad libitum whole milk prior to weaning and prepubertal protein supplementation on skeletal growth rate and first-lactation milk production. Journal of Dairy Science 93(6):2639-2650.

Mohd Nor, N., W. Steeneveld, T. van Werven, M. C. M. Mourits, and H. Hogeveen. 2013. First-calving age and first-lactation milk production on Dutch dairy farms. Journal of Dairy Science 96(2):981-992.

Mohd Nor, N., W. Steeneveld, T. H. J. Derkman, M. D. Verbruggen, A. G. Evers, M. H. A. de Haan, and H. Hogeveen. 2015. The total cost of rearing a heifer on Dutch dairy farms: calculated versus perceived cost. Irish Veterinary Journal 68(1):29.

Montoro, C., E. Miller-Cushon, T. DeVries, and A. Bach. 2013. Effect of physical form of forage on performance, feeding behaviour, and digestibility of Holstein calves. Journal of dairy science 96(2):1117-1124.

Moore, D. A., J. Taylor, M. L. Hartman, and W. M. Sischo. 2009. Quality assessments of waste milk at a calf ranch. Journal of Dairy Science 92(7):3503-3509.

Moore, M., J. W. Tyler, M. Chigerwe, M. E. Dawes, and J. R. Middleton. 2005. Effect of delayed colostrum collection on colostral IgG concentration in dairy cows. Journal of the American Veterinary Medical Association 226(8):1375-1377.

Moran, j. 2012. Rearing young stock on tropical dairy farms in Asia. Csiro publishing.

Moran, J. and P. Chamberlain. 2017. Blueprints for Tropical Dairy Farming: Increasing Domestic Milk Production in Developing Countries. Csiro publishing.

Morin, D., G. McCoy, and W. Hurley. 1997. Effects of quality, quantity, and timing of colostrum feeding and addition of a dried colostrum supplement on immunoglobulin G1 absorption in Holstein bull calves. Journal of dairy science 80(4):747-753.

Morin, D. E., S. V. Nelson, E. D. Reid, D. W. Nagy, G. E. Dahl, and P. D. Constable. 2010. Effect of colostral volume, interval between calving and first milking, and photoperiod on colostral IgG concentrations in dairy cows. Journal of the American Veterinary Medical Association 237(4):420-428.

Morrill, K., E. Conrad, A. Lago, J. Campbell, J. Quigley, and H. Tyler. 2012. Nationwide evaluation of quality and composition of colostrum on dairy farms in the United States. Journal of dairy science 95(7):3997-4005.

Morrison, S. J., H. Wicks, R. Fallon, J. Twigge, L. Dawson, A. Wylie, and A. Carson. 2009a. Effects of feeding level and protein content of milk replacer on the performance of dairy herd replacements. Animal: an international journal of animal bioscience 3(11):1570.

Morrison, S., A. F. Carson, D. Matthews, and M. Mulholland. 2009b. An investigation of calf rearing practices on dairy farms in Northern Ireland. Proceedings of the British Society of Animal Science 2009:84-84.

Morrison, S., H. Wicks, A. Carson, R. Fallon, J. Twigge, D. Kilpatrick, and S. Watson. 2012. The effect of calf nutrition on the performance of dairy herd replacements. Animal 6(6):909-919.

Morton, J. M. 2010. Interrelationships between herd-level reproductive performance measures based on intervals from initiation of the breeding program in year-round and seasonal calving dairy herds. Journal of Dairy Science 93(3):901-910.

Mossa, F., S. W. Walsh, S. T. Butler, D. P. Berry, F. Carter, P. Lonergan, G. W. Smith, J. J. Ireland, and A. C. O. Evans. 2012. Low numbers of ovarian follicles ≥3mm in diameter are associated with low fertility in dairy cows. Journal of Dairy Science 95(5):2355-2361.

Mousel, E., R. A. Cushman, G. Perry, and L. Kill. 2014. Effect of heifer calving date on longevity and lifetime productivity. https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1023&context=driftlessconference.

Muller, L. and D. Ellinger. 1981. Colostral immunoglobulin concentrations among breeds of dairy cattle. Journal of Dairy Science 64(8):1727-1730.

Mulligan, F., L. O’Grady, D. Rice, and M. Doherty. 2006. A herd health approach to dairy cow nutrition and production diseases of the transition cow. Animal Reproduction Science 96(3-4):331-353.

Murphy, J. 1999. Effect of dry period protein feeding on post-partum milk production and composition. Livestock Production Science 57(2):169-179.

Neave, H. W., J. H. Costa, D. M. Weary, and M. A. von Keyserlingk. 2018. Personality is associated with feeding behaviour and performance in dairy calves. Journal of dairy science 101(8):7437-7449.

Nejad, J. G., A. Hosseindoust, A. Shoae, B. Ghorbani, B. H. Lee, E. Oskoueian, D. Hajilari, A. Amouzmehr, J. D. Lohakare, and K. I. Sung. 2013. Effects of feeding levels of starter on weaning age, performance, nutrient digestibility and health parameters in Holstein dairy calves. Asian-Australasian journal of animal sciences 26(6):827-830

Nieuwhof, G., R. Powell, and H. Norman. 1989. Ages at calving and calving intervals for dairy cattle in the United States. Journal of Dairy Science 72(3):685-692.

NRC. 2001. Nutrient requirements of dairy cattle. National Academy Press, Washington, DC.

O’Callaghan, T. F., D. Mannion, D. Apopei, N. A. McCarthy, S. A. Hogan, K. N. Kilcawley, and M. Egan. 2019. Influence of supplemental feed choice for pasture-based cows on the fatty acid and volatile profile of milk. Foods 8(4):137.

O'Callaghan, T. F., M. O'Donovan, J. P. Murphy, K. Sugrue, D. Mannion, W. P. McCarthy, M. Timlin, K. N. Kilcawley, R. M. Hickey, and J. T. Tobin. 2020. Evolution of the bovine milk fatty acid profile – From colostrum to milk five days post parturition. International Dairy Journal 104:104655.

O'Connell, J. M., P. S. Giller, and W. J. Meaney. 1993. Weanling training and cubicle usage as heifers. Applied Animal Behaviour Science 37(3):185-195.

O'Donovan, M. and L. Delaby. 2008. Sward characteristics, grass dry matter intake and milk production performance is affected by timing of spring grazing and subsequent stocking rate. Livestock Science 115(2-3):158-168.

O'Donovan, M. and P. Dillon. 1999. Measurement of grassland management practice on commercial dairy farms. Teagasc.

O'Donovan, M., E. Lewis, and P. O'Kiely. 2011. Requirements of future grass-based ruminant production systems in Ireland. Irish Journal of Agricultural and Food Research: 1-21.

O'Donovan, M., P. Dillon, M. Rath, and G. Stakelum. 2002. A comparison of four methods of herbage mass estimation. Irish Journal of Agricultural and Food Research: 17-27.

O'Driscoll, K., L. Boyle, and A. Hanlon. 2009. The effect of breed and housing system on dairy cow feeding and lying behaviour. Applied animal behaviour science 116(2-4):156-162.

O'Neill, B., E. Lewis, M. O'Donovan, L. Shalloo, N. Galvin, F. Mulligan, T. Boland, and R. Delagarde. 2013. Predicting grass dry matter intake, milk yield and milk fat and protein yield of spring calving grazing dairy cows during the grazing season. Animal 7(8):1379-1389.

O'Sullivan, M., B. Horan, K. M. Pierce, S. McParland, K. O'Sullivan, and F. Buckley. 2019. Milk production of Holstein-Friesian cows of divergent Economic Breeding Index evaluated under seasonal pasture-based management. Journal of Dairy Science 102(3):2560-2577.

Overton, M. and K. Dhuyvetter. 2017. Economic considerations regarding the raising of dairy replacement heifers. Large Dairy Herd Management. Champaign, IL: American Dairy Science Association: 457-474.

Owens, D., M. McGee, and T. Boland. 2008. Effect of grass regrowth interval on intake, rumen digestion and nutrient flow to the omasum in beef cattle. Animal feed science and technology 146(1-2):21-41.

Palmer, M. A., G. Olmos, L. A. Boyle, and J. F. Mee. 2010. Estrus detection and estrus characteristics in housed and pastured Holstein–Friesian cows. Theriogenology 74(2):255-264.

Paputungan, U., L. Hakim, G. Ciptadi, and H. Lapian. 2015. Application of body volume formula for predicting live weight in Ongole crossbred cows. International Journal of Livestock Production 6(3):35-40.

Park, C., R. Danielson, B. Kreft, S. Kim, Y. Moon, and W. Keller. 1998. Nutritionally directed compensatory growth and effects on lactation potential of developing heifers. Journal of dairy science 81(1):243-249.

Patterson R., Morrison S., L. S., and T. K. 2018. The effect of pasture allowance on the performance of growing dairy heifers. Grassland Science in Europe 23. Accessed on 7 September 2021. https://www.cabdirect.org/cabdirect/FullTextPDF/2018/20183254284.pdf

Patterson, D. J., R. C. Perry, G. H. Kiracofe, R. A. Bellows, R. B. Staigmiller, and L. R. Corah. 1992. Management considerations in heifer development and puberty. Journal of animal science 70(12):4018-4035.

Patterson, D., L. Corah, G. Kiracofe, J. Stevenson, and J. Brethour. 1989. Conception rate in Bos Taurus and Bos Indicus crossbred heifers after postweaning energy manipulation and synchronization of estrus with melengestrol acetate and fenprostalene. Journal of animal science 67(5):1138-1147.

Patterson, R. and S. Morrison. 2019. An investigation into precision supplementation of concentrates to grazing Holstein heifers. Precision livestock farming'19:753.

Patton, D., K. Pierce, and B. Horan. 2016. Effect of stocking rate on milk and pasture productivity and supplementary feed use for spring calving pasture fed dairy systems. Journal of dairy science 99(7):5904-5915.

Pereira, G. R., J. O. J. Barcellos, A. G. Sessim, J. U. Tarouco, F. D. Feijó, J. Braccini Neto, Ê. R. Prates, and M. E. A. Canozzi. 2017. Relationship of post-weaning growth and age at puberty in crossbred beef heifers. Revista Brasileira de Zootecnia 46:413-420.

Pezeshki, A., A. Capuco, B. De Spiegeleer, L. Peelman, M. Stevens, R. Collier, and C. Burvenich. 2010. An integrated view on how the management of the dry period length of lactating cows could affect mammary biology and defence. Journal of animal physiology and animal nutrition 94(5):e7-e30.

Phillips, C. J. C. 2004. The Effects of Forage Provision and Group Size on the Behaviour of Calves. Journal of Dairy Science 87(5):1380-1388.

Pirlo, G., F. Miglior, and M. Speroni. 2000. Effect of age at first calving on production traits and on difference between milk yield returns and rearing costs in Italian Holsteins. Journal of dairy science 83(3):603-608.

Pollock, J. G., A. W. Gordon, K. M. Huson, and D. A. McConnell. 2020. The Effect of Frequency of Fresh Pasture Allocation on Pasture Utilization and the Performance of High Yielding Dairy Cows. Animals 10(11):2176.

Poncheki, J. K., M. L. S. Canha, S. L. Viechnieski, and R. d. Almeida. 2015. Analysis of daily body weight of dairy cows in early lactation and associations with productive and reproductive performance. Revista Brasileira de Zootecnia 44(5):187-192.

Prendiville, R., K. Pierce, and F. Buckley. 2009. An evaluation of production efficiencies among lactating Holstein-Friesian, Jersey, and Jersey× Holstein-Friesian cows at pasture. Journal of Dairy Science 92(12):6176-6185.

Prendiville, R., E. Lewis, K. M. Pierce, and F. Buckley. 2010. Comparative grazing behaviour of lactating Holstein-Friesian, Jersey, and Jersey × Holstein-Friesian dairy cows and its association with intake capacity and production efficiency. Journal of Dairy Science 93(2):764-774.

Prendiville, R., K. Pierce, L. Delaby, and F. Buckley. 2011a. Animal performance and production efficiencies of Holstein-Friesian, Jersey and Jersey× Holstein-Friesian cows throughout lactation. Livestock Science 138(1-3):25-33.

Prendiville, R., L. Shalloo, K. Pierce, and F. Buckley. 2011b. Comparative performance and economic appraisal of Holstein-Friesian, Jersey and Jersey x Holstein-Friesian cows under seasonal pasture-based management. Irish Journal of Agricultural and Food Research: 123-140.

Pritchard, T., M. Coffey, R. Mrode, and E. Wall. 2013. Genetic parameters for production, health, fertility and longevity traits in dairy cows. Animal 7(1):34-46.

Pritchett, L. C., C. C. Gay, T. E. Besser, and D. D. Hancock. 1991. Management and production factors influencing immunoglobulin G1 concentration in colostrum from Holstein cows. Journal of dairy science 74(7):2336-2341.

Pryce, J., M. Coffey, and G. Simm. 2001. The relationship between body condition score and reproductive performance. Journal of Dairy Science 84(6):1508-1515.

Pyo, J., S. Pletts, J. Romao, Y. Inabu, Z. He, D. Haines, T. Sugino, L. Guan, and M. Steele. 2018. The effects of extended colostrum feeding on gastrointestinal tract growth of the neonatal dairy calf. Journal of Animal Science 96:170-171.

Quigley, J. 1985. Development of equations to predict dry matter intake of dairy heifers. Virginia Polytechnic Institute and State University.

Quigley, J., R. James, and M. McGilliard. 1986a. Dry matter intake in dairy heifers. 1. Factors affecting intake of heifers under intensive management. Journal of Dairy Science 69(11):2855-2862.

Quigley, J., R. James, and M. McGilliard. 1986b. Dry matter intake in dairy heifers. 2. Equations to predict intake of heifers under intensive management. Journal of Dairy Science 69(11):2863-2867.

Quigley, J., K. Martin, D. Bemis, L. Potgieter, C. Reinemeyer, B. Rohrbach, H. Dowlen, and K. Lamar. 1995. Effects of housing and colostrum feeding on serum immunoglobulins, growth, and fecal scores of Jersey calves. Journal of Dairy Science 78(4):893-901.

Quigley, J. D., A. Lago, C. Chapman, P. Erickson, and J. Polo. 2013. Evaluation of the Brix refractometer to estimate immunoglobulin G concentration in bovine colostrum. Journal of Dairy Science 96(2):1148-1155.

Quintana, E. D. L., A. Mendoza, C. Cajarville, O. Bentancur, and J. L. Repetto. 2018. Post-weaning feeding levels on feeding behaviour, growth and development in Holstein dairy heifers. Ciência Rural 48(3).

Raeth-Knight, M., H. Chester-Jones, S. Hayes, J. Linn, R. Larson, D. Ziegler, B. Ziegler, and N. Broadwater. 2009. Impact of conventional or intensive milk replacer programs on Holstein heifer performance through six months of age and during first lactation. Journal of Dairy Science 92(2):799-809.

Ramsbottom, G. 2020. Trends in genetic merit for dairy cow fertility. Veterinary Ireland Journal Volume 10 Number 8.

Ramsbottom, G., B. Horan, D. P. Berry, and J. R. Roche. 2015. Factors associated with the financial performance of spring-calving, pasture-based dairy farms. Journal of Dairy Science 98(5):3526-3540.

Rastani, R., R. Grummer, S. Bertics, A. Gümen, M. Wiltbank, D. Mashek, and M. Schwab. 2005. Reducing dry period length to simplify feeding transition cows: Milk production, energy balance, and metabolic profiles. Journal of dairy science 88(3):1004-1014.

Reddy, P. R. K., J. Raju, A. Reddy, P. Reddy, and I. Hyder. 2016. Transition period and its successful management in dairy cows. Indian J. Nat. Sci 7(38):11691-11699.

Reid, M., M. O'Donovan, J. Murphy, C. Fleming, E. Kennedy, and E. Lewis. 2015. The effect of high and low levels of supplementation on milk production, nitrogen utilization efficiency, and milk protein fractions in late-lactation dairy cows. Journal of dairy science 98(8):5529-5544.

Reis, G. L., F. H. M. A. R. Albuquerque, B. D. Valente, G. A. Martins, R. L. Teodoro, M. B. D. Ferreira, J. B. N. Monteiro, M. d. A. Silva, and F. E. Madalena. 2008. Prediction of live weight based on body measurements in crossbred animals Holstein/Gir. Ciência Rural 38(3):778-783.

Reschke, C., E. Schelling, A. Michel, F. Remy-Wohlfender, and M. Meylan. 2017. Factors associated with colostrum quality and effects on serum gamma globulin concentrations of calves in Swiss dairy herds. Journal of veterinary internal medicine 31(5):1563-1571.

Rincker, L. D., M. VandeHaar, C. Wolf, J. Liesman, L. Chapin, and M. W. Nielsen. 2011. Effect of intensified feeding of heifer calves on growth, pubertal age, calving age, milk yield, and economics. Journal of Dairy Science 94(7):3554-3567.

Robinson, P., J. Moorby, and D. D. Gisi. 2009. Colostrum production by primiparous and multiparous Holstein dairy cows and its usefulness as an estimator of full lactation milk yield. Livestock Science 125:323–325.

Robison, J. D., G. Stott, and S. DeNise. 1988. Effects of passive immunity on growth and survival in the dairy heifer. Journal of dairy science 71(5):1283-1287.

Roche, J. R. 2007a. Milk production responses to pre-and post-calving dry matter intake in grazing dairy cows. Livestock Science 110(1-2):12-24.

Roche, J. R., J. M. Lee, K. A. Macdonald, and D. P. Berry. 2007b. Relationships among Body Condition Score, Body Weight, and Milk Production Variables in Pasture-Based Dairy Cows. Journal of Dairy Science 90(8):3802-3815.

Roche, J., K. Macdonald, C. Burke, J. Lee, and D. Berry. 2007c. Associations among body condition score, body weight, and reproductive performance in seasonal-calving dairy cattle. Journal of Dairy Science 90(1):376-391.

Roche, J. R., N. C. Friggens, J. K. Kay, M. W. Fisher, K. J. Stafford, and D. P. Berry. 2009. Invited review: Body condition score and its association with dairy cow productivity, health, and welfare. Journal of dairy science 92(12):5769-5801.

Roche, J., N. Dennis, K. Macdonald, C. Phyn, P. Amer, R. White, and J. Drackley. 2015. Growth targets and rearing strategies for replacement heifers in pasture-based systems: a review. Animal Production Science 55(7):902-915.

Roche, S., D. Renaud, R. Genore, D. Shock, C. Bauman, S. Croyle, H. Barkema, J. Dubuc, G. Keefe, and D. Kelton. 2020. Canadian National Dairy Study: Describing Canadian dairy producer practices and perceptions surrounding cull cow management. Journal of dairy science 103(4):3414-3421.

Rook, A. 2000. Principles of foraging and grazing behaviour. Grass: its production and utilization. A. Hopkins, ed. Blackwell Science: 229.

Rosenberger, K., J. Costa, H. Neave, M. von Keyserlingk, and D. Weary. 2017. The effect of milk allowance on behaviour and weight gains in dairy calves. Journal of dairy science 100(1):504-512.

Roth, B. A., N. M. Keil, L. Gygax, and E. Hillmann. 2009. Influence of weaning method on health status and rumen development in dairy calves. J Dairy Sci 92(2):645-656.

Ruelle, E., D. Hennessy, and L. Delaby. 2018. Development of the Moorepark St Gilles grass growth model (MoSt GG model): A predictive model for grass growth for pasture based systems. European Journal of Agronomy 99:80-91.

Ruelle, E., L. Delaby, and L. Shalloo. 2019. Linkage between predictive transmitting ability of a genetic index, potential milk production, and a dynamic model. Journal of dairy science 102(4):3512-3522.

Sander, E., R. Warner, H. Harrison, and J. Loosli. 1959. The stimulatory effect of sodium butyrate and sodium propionate on the development of rumen mucosa in the young calf. Journal of dairy science 42(9):1600-1605.

Sasaki, M., C. Davis, and B. Larson. 1976. Production and turnover of IgG1 and IgG2 immunoglobulins in the bovine around parturition. Journal of Dairy Science 59(12):2046-2055.

Savian, J. V., T. C. M. Genro, A. B. Neto, C. Bremm, E. B. Azevedo, D. B. David, H. L. Gonda, and P. C. F. Carvalho. 2018. Comparison of faecal crude protein and n-alkanes techniques to estimate herbage intake by grazing sheep. Animal Feed Science and Technology 242:144-149.

Sawa, A., K. Siatka, and S. Krężel-Czopek. 2019. Effect of age at first calving on first lactation milk yield, lifetime milk production and longevity of cows. Annals of animal science 19(1):189-200.

Schäff, C. T., J. Gruse, J. Maciej, M. Mielenz, E. Wirthgen, A. Hoeflich, M. Schmicke, R. Pfuhl, P. Jawor, and T. Stefaniak. 2016. Effects of feeding milk replacer ad libitum or in restricted amounts for the first five weeks of life on the growth, metabolic adaptation, and immune status of newborn calves. PloS one 11(12):e0168974.

Schütz, K., K. Clark, N. Cox, L. Matthews, and C. Tucker. 2010. Responses to short-term exposure to simulated rain and wind by dairy cattle: time budgets, shelter use, body temperature and feed intake. Animal Welfare 19(4):375.

Sejrsen, K. 2005. Mammary development and milk yield potential. Calf and heifer rearing: principles of rearing the modern dairy heifer from calf to calving. 60th University of Nottingham Easter School in Agricultural Science, Nottingham, UK. 23rd-24th March 2004:237-251.

Seymour, D. J., A. Cánovas, C. F. Baes, T. C. S. Chud, V. R. Osborne, J. P. Cant, L. F. Brito, B. Gredler-Grandl, R. Finocchiaro, R. F. Veerkamp, Y. de Haas, and F. Miglior. 2019. Invited review: Determination of large-scale individual dry matter intake phenotypes in dairy cattle. Journal of Dairy Science 102(9):7655-7663.

Shalloo, L., A. Cromie, and N. McHugh. 2014. Effect of fertility on the economics of pasture-based dairy systems. Animal 8(s1):222-231.

Shalloo, L., A. Ryan, and P. French. 2012. Getting ready for Expansion! Lessons from the Greenfield project. Page 9-23 Accessed on 7 September 2021 https://www.teagasc.ie/media/website/publications/2012/National_Dairy_Conference_2012.pdf.

Shalloo, L., S. O'Donnell, and B. Horan. 2007. Profitable dairying in an increased EU milk quota scenario. Pages 20-44 in Proc. National Dairy Conference, November 21 and 22 Kilkenny and Mayo, Teagasc, Ireland.

Shamay, A., D. Werner, U. Moallem, H. Barash, and I. Bruckental. 2005. Effect of nursing management and skeletal size at weaning on puberty, skeletal growth rate, and milk production during first lactation of dairy heifers. Journal of Dairy Science 88(4):1460-1469.

Shelley, A., D. Lau, A. Stone, and J. Bewley. 2016. Measuring feed volume and weight by machine vision. Journal of dairy science 99(1):386-391.

Sherwin, V., C. Hudson, A. Henderson, and M. J. Green. 2016. The association between age at first calving and survival of first lactation heifers within dairy herds. Animal 10(11):1877-1882.

Shrestha, H. K., T. Nakao, T. Higaki, T. Suzuki, and M. Akita. 2004. Resumption of postpartum ovarian cyclicity in high-producing Holstein cows. Theriogenology 61(4):637-649.

Sieber, M., Freeman, A., & Kelley, D. (1989). Effects of body measurements and weight on calf size and calving difficulty of Holsteins. Journal of Dairy Science, 72(9), 2402-2410.

Silva, A. L., T. J. DeVries, E. C. Fernandes, and M. I. Marcondes. 2021. Short communication: Development and evaluation of equations to predict growth of Holstein dairy heifers in a tropical climate. Journal of Dairy Science 104(1):525-531.

Silva, L. G. T., R. F. Cooke, K. M. Schubach, A. P. Brandão, R. S. Marques, T. F. Schumaher, P. Moriel, and D. W. Bohnert. 2018. Supplementing a yeast-derived product to enhance productive and health responses of beef steers. Animal 12(8):1576-1583.

Sinclair, K., P. Garnsworthy, G. Mann, and L. Sinclair. 2014. Reducing dietary protein in dairy cow diets: Implications for nitrogen utilization, milk production, welfare and fertility. Animal 8(2):262-274.

Soberon, F., E. Raffrenato, R. W. Everett, and M. E. Van Amburgh. 2012a. Preweaning milk replacer intake and effects on long-term productivity of dairy calves. Journal of Dairy Science 92(2):783–793.

Soberon, F., M. Van Amburgh, D. Lopez, J. Karszes, and R. Everett. 2012b. Early Life Nutrition and Management Impacts Long-Term Productivity of Calves. Accessed on 7 September 2021. https://conservancy.umn.edu/bitstream/handle/11299/204310/SF95_M658a-73-2012_magr56303.pdf?sequence=1&isAllowed=y.

Soberon, F. and M. E. Van Amburgh. 2013. LACTATION BIOLOGY SYMPOSIUM: The effect of nutrient intake from milk or milk replacer of preweaned dairy calves on lactation milk yield as adults: A meta-analysis of current data1. Journal of Animal Science 91(2):706-712.

Soberon, F. and M. E. Van Amburgh. 2017. Effects of preweaning nutrient intake in the developing mammary parenchymal tissue. Journal of Dairy Science 100(6):4996-5004.

Sprott, L. R. and B. B. Carpenter. 2007. Synchronizing estrus in cattle. Texas FARMER Collection.

Stakelum, G. and J. Connolly. 1987. Effect of Body Size and Milk Yield on Intake of Fresh Herbage by Lactating Dairy Cows Indoors. Irish Journal of Agricultural Research 26(1):9-22.

Stallings, C. C., G. Kroll, J. C. Kelley, and M. L. McGilliard. 1985. A Computer Ration Evaluation Program for Heifers, Dry Cows, and Lactating Cows. Journal of Dairy Science 68(4):1015-1019.

Steele, M. A., J. H. Doelman, L. N. Leal, F. Soberon, M. Carson, and J. A. Metcalf. 2017. Abrupt weaning reduces postweaning growth and is associated with alterations in gastrointestinal markers of development in dairy calves fed an elevated plane of nutrition during the preweaning period. J Dairy Sci 100(7):5390-5399.

Stelwagen, K., E. Carpenter, B. Haigh, A. Hodgkinson, and T. Wheeler. 2009. Immune components of bovine colostrum and milk. Journal of animal science 87(suppl_13):3-9.

Stewart, S., S. Godden, R. Bey, P. Rapnicki, J. Fetrow, R. Farnsworth, M. Scanlon, Y. Arnold, L. Clow, and K. Mueller. 2005. Preventing bacterial contamination and proliferation during the harvest, storage, and feeding of fresh bovine colostrum. Journal of Dairy Science 88(7):2571-2578.

Stobo, I., J. Roy, and H. J. Gaston. 1966. Rumen development in the calf: 2. The effect of diets containing different proportions of concentrates to hay on digestive efficiency. British Journal of Nutrition 20(2):189-215.

Stott, G., D. Marx, B. Menefee, and G. Nightengale. 1979a. Colostral immunoglobulin transfer in calves I. Period of absorption. Journal of dairy science 62(10):1632-1638.

Stott, G., D. Marx, B. Menefee, and G. Nightengale. 1979b. Colostral immunoglobulin transfer in calves II. The rate of absorption. Journal of dairy science 62(11):1766-1773.

Stott, G., W. Fleenor, and W. Kleese. 1981. Colostral immunoglobulin concentration in two fractions of first milking postpartum and five additional milkings. Journal of dairy science 64(3):459-465.

Swatland, H. J. 1994. Structure and development of meat animals and poultry. CRC Press.

Sweeney, B. C., J. Rushen, D. M. Weary, and A. M. de Passillé. 2010. Duration of weaning, starter intake, and weight gain of dairy calves fed large amounts of milk. J Dairy Sci 93(1):148-152.

Taylor, S. and H. Fitzhugh. 1971. Genetic relationships between mature weight and time taken to mature within a breed. Journal of Animal Science 33(4):726-731.

Teagasc. 2015. Moorepark'15 Irish Dairying – Sustainable Expansion. Pages 15-18.

Teagasc. 2016a. Teagasc Beef Manual. Accessed 7 September 2021. https://www.teagasc.ie/media/website/publications/2016/Beef-Manual-Section8.pdf.

Teagasc. 2016b. Teagasc Technology Foresight: Technology Transforming Irish Agri-Food and Bio-Economy. Teagasc Agriculture and Food Development Authority: Carlow, Ireland.

Teagasc. 2017. Teagasc Calf Rearing Manual. https://www.teagasc.ie/media/website/publications/2017/Section3-Milk-feeding.pdf

Tebug, S. F., A. Missohou, S. Sourokou Sabi, J. Juga, E. J. Poole, M. Tapio, and K. Marshall. 2018. Using body measurements to estimate live weight of dairy cattle in low-input systems in Senegal. Journal of Applied Animal Research 46(1):87-93.

Tekerli, M., Z. Akinci, I. Dogan, and A. Akcan. 2000. Factors affecting the shape of lactation curves of Holstein cows from the Balikesir province of Turkey. Journal of Dairy Science 83(6):1381-1386.

Tenhagen, B. A., A. Helmbold, and W. Heuwieser. 2007. Effect of various degrees of dystocia in dairy cattle on calf viability, milk production, fertility and culling. Journal of Veterinary Medicine Series A 54(2):98-102.

Terré, M., C. Tejero, and A. Bach. 2009. Long-term effects on heifer performance of an enhanced-growth feeding programme applied during the preweaning period. Journal of Dairy Research 76(3):331-339.

Thompson, J., E. Pollak, and C. Pelissier. 1983. Interrelationships of parturition problems, production of subsequent lactation, reproduction, and age at first calving. Journal of Dairy Science 66(5):1119-1127.

Tozer, P. and A. Heinrichs. 2001. What Affects the Costs of Raising Replacement Dairy Heifers: A Multiple-Component Analysis? Journal of Dairy Science 84(8):1836-1844.

Trevaskis, L. M., W. J. Fulkerson, and K. S. Nandra. 2004. Effect of time of feeding carbohydrate supplements and pasture on production of dairy cows. Livestock Production Science 85(2):275-285.

Troccon, J. L. 1993. Effects of winter-feeding during the rearing period on performance and longevity in dairy cattle. Livestock Production Science 36(2):157-176.

Urie, N., J. Lombard, C. Shivley, C. Kopral, A. Adams, T. Earleywine, J. Olson, and F. Garry. 2018. Preweaned heifer management on US dairy operations: Part I. Descriptive characteristics of preweaned heifer raising practices. Journal of dairy science 101(10):9168-9184.

USDA. 2011. Dairy Heifer Raiser, 2011. An overview of operations that specialize in dairy heifers. https://www.aphis.usda.gov/animal_health/nahms/dairy/downloads/dairyheifer11/HeiferRaiser_1.pdf

USDA. 2014. Dairy Cattle Management Practices in the United States, 2014. Accessed 7 September 2021 https://www.aphis.usda.gov/animal_health/nahms/dairy/downloads/dairy14/Dairy14_dr_PartI_1.pdf

Van Amburgh, M. E., E. A. Collao-Saenz, R. J. Higgs, D. A. Ross, E. B. Recktenwald, E. Raffrenato, L. E. Chase, T. R. Overton, J. K. Mills, and A. Foskolos. 2015. The Cornell Net Carbohydrate and Protein System: Updates to the model and evaluation of version 6.5. Journal of Dairy Science 98(9):6361-6380.

Van Amburgh, M., D. Galton, D. Bauman, R. Everett, D. Fox, L. Chase, and H. Erb. 1998. Effects of three prepubertal body growth rates on performance of Holstein heifers during first lactation. Journal of Dairy Science 81(2):527-538.

Van Amburgh, M., F. Soberon, J. Karszes, and R. Everett. 2014. Early life nutrition and management impacts long-term productivity of calves. Accessed on 7 September 2021. https://ecommons.cornell.edu/bitstream/handle/1813/36500/1.VanAmburgh.Manuscript.pdf;sequence=1.

Van Amburgh, M., T. Overton, L. Chase, D. Ross, and E. Recktenwald. 2009. The Cornell Net Carbohydrate and Protein System: Current and future approaches for balancing of amino acids. Pages 28-37 in Proc. Proceedings of Cornell Nutrition Conference for Feed Manufacturers, Syracuse, NY. New York State College of Agriculture & Life Sciences, Cornell University.

Van Dyne, G., N. Brockington, Z. Szocs, J. Duek, and C. Ribic. 1980. Large herbivore subsystem. Large herbivore subsystem: 269-537.

van Soest, B., F. Cullens, M. VandeHaar, and M. W. Nielsen. 2020. Effects of transition milk and milk replacer supplemented with colostrum replacer on growth and health of dairy calves. Journal of Dairy Science 103(12):12104-12108.

Vance, E. R., C. P. Ferris, C. T. Elliott, H. M. Hartley, and D. J. Kilpatrick. 2013. Comparison of the performance of Holstein-Friesian and Jersey×Holstein-Friesian crossbred dairy cows within three contrasting grassland-based systems of milk production. Livestock Science 151(1):66-79.

Vasseur, E., F. Borderas, R. I. Cue, D. Lefebvre, D. Pellerin, J. Rushen, K. M. Wade, and A. M. de Passillé. 2010. A survey of dairy calf management practices in Canada that affect animal welfare. Journal of Dairy Science 93(3):1307-1316.

Veerkamp, R., P. Dillon, E. Kelly, A. Cromie, and A. Groen. 2002. Dairy cattle breeding objectives combining yield, survival, and calving interval for pasture-based systems in Ireland under different milk quota scenarios. Livestock Production Science 76(1-2):137-151.

Vendramini, J., L. Sollenberger, J. Dubeux Jr, S. Interrante, R. Stewart Jr, and J. Arthington. 2007. Concentrate supplementation effects on the performance of early-weaned calves grazing Tifton 85 Bermuda grass. Agronomy Journal 99(2):399-404.

Waage, S., H. Skei, J. Rise, T. Rogdo, S. Sviland, and S. Ødegaard. 2000. Outcome of clinical mastitis in dairy heifers assessed by re-examination of cases one month after treatment. Journal of dairy science 83(1):70-76.

Wade, 1991. Factors affecting the availability of vegetative lolium perenne to grazing dairy cows with special reference to sward characteristics, stocking rate and grazing method. PhD thesis. University of Rennes, France.

Waghorn, G. and D. Clark. 2004. Feeding value of pastures for ruminants. New Zealand Veterinary Journal 52(6):320-331.

Walsh, S., F. Buckley, K. Pierce, N. Byrne, J. Patton, and P. Dillon. 2008. Effects of breed and feeding system on milk production, body weight, body condition score, reproductive performance, and postpartum ovarian function. Journal of Dairy Science 91(11):4401-4413.

Washburn, S. P., S. L. White, J. T. Green, and G. A. Benson. 2002. Reproduction, Mastitis, and Body Condition of Seasonally Calved Holstein and Jersey Cows in Confinement or Pasture Systems. Journal of Dairy Science 85(1):105-111.

Washburn, S., W. Silvia, C. Brown, B. McDaniel, and A. McAllister. 2002. Trends in reproductive performance in southeastern Holstein and Jersey DHI herds. Journal of Dairy Science 85(1):244-251.

Wathes, D., G. Pollott, K. Johnson, H. Richardson, and J. Cooke. 2014. Heifer fertility and carry over consequences for lifetime production in dairy and beef cattle. Animal 8(s1):91-104.

Wathes, D., J. Brickell, N. Bourne, A. Swali, and Z. Cheng. 2008. Factors influencing heifer survival and fertility on commercial dairy farms. Animal 2(8):1135-1143.

Weaver, D. M., J. W. Tyler, D. C. VanMetre, D. E. Hostetler, and G. M. Barrington. 2000. Passive Transfer of Colostral Immunoglobulins in Calves. Journal of Veterinary Internal Medicine 14(6):569-577.

Wickramasinghe, H. K. J. P., A. J. Kramer, and J. A. D. R. N. Appuhamy. 2019. Drinking water intake of newborn dairy calves and its effects on feed intake, growth performance, health status, and nutrient digestibility. Journal of Dairy Science 102(1):377-387.

Wildman, E., G. Jones, P. Wagner, R. Boman, H. Troutt Jr, and T. Lesch. 1982. A dairy cow body condition scoring system and its relationship to selected production characteristics. Journal of Dairy Science 65(3):495-501.

Wilmink, J. 1987. Adjustment of test-day milk, fat and protein yield for age, season and stage of lactation. Livestock Production Science 16(4):335-348.

Wims, C. M., M. H. Deighton, E. Lewis, B. O’Loughlin, L. Delaby, T. M. Boland, and M. O’Donovan. 2010. Effect of pre-grazing herbage mass on methane production, dry matter intake, and milk production of grazing dairy cows during the mid-season period1. Journal of Dairy Science 93(10):4976-4985.

Wims, C., M. McEvoy, L. Delaby, T. Boland, and M. O'Donovan. 2013. Effect of perennial ryegrass (Lolium perenne L.) cultivars on the milk yield of grazing dairy cows. Animal 7(3):410-421.

Wingler, A. and D. Hennessy. 2016. Limitation of Grassland Productivity by Low Temperature and Seasonality of Growth. Frontiers in Plant Science 7(1130).

Wright, M., E. Lewis, B. Garry, N. Galvin, F. Dunshea, M. Hannah, M. J. Auldist, W. Wales, P. Dillon, and E. Kennedy. 2019. Evaluation of the n-alkane technique for estimating herbage dry matter intake of dairy cows offered herbage harvested at two different stages of growth in summer and autumn. Animal Feed Science and Technology 247:199-209.

Zanton, G. I. and A. J. Heinrichs. 2007. The Effects of Controlled Feeding of a High-Forage or High-Concentrate Ration on Heifer Growth and First-Lactation Milk Production1. Journal of Dairy Science 90(7):3388-3396.

Zanton, G. and A. J. Heinrichs. 2008a. Rumen digestion and nutritional efficiency of dairy heifers limit-fed a high forage ration to four levels of dry matter intake. Journal of dairy science 91(9):3579-3588.

Zanton, G. and J. Heinrichs. 2008b. Precision feeding dairy heifers: Strategies and recommendations. College of Agricultural Sciences, DAS: 08-130.

Chapter 10: List of Outputs

10.1 Papers Published in Peer-Reviewed Scientific Articles

Costigan, H., L. Delaby, S. Walsh, B. Lahart, and E. Kennedy. 2021. The development of equations to predict live-weight from linear body measurements of pasture-based Holstein-Friesian and Jersey dairy heifers. Livestock Science: 104693.

Livestock Science 253 (2021) 104693

Contents lists available at ScienceDirect

Livestock Science

journal homepage: www.elsevier.com/locate/livsci

Short communication

The development of equations to predict live-weight from linear body measurements of pasture-based Holstein-Friesian and Jersey dairy heifers

H. Costigan [a,b], L. Delaby [c], S. Walsh [b], B. Lahart [a], E. Kennedy [a,*]

[a] Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland
[b] Waterford Institute of Technology, Cork Road, Waterford, Co. Waterford, Ireland
[c] INRAE, Agrocampus Ouest, UMR Physiologie, Environnement et Génétique pour l'Animal et les Systèmes d'Elevage, 35590 St-Gilles, France

HIGHLIGHTS

- In the absence of a weighing scales live-weight of Holstein-Friesian and Jersey heifers can be successfully predicted using body length, heart girth and withers height and their combinations.
- Regression equations of live-weight on heart girth, body volume and a polynomial of length, girth, and height equations, respectively, were accurate predictors of live-weight for pasture-based dairy heifers ($R^2 > 0.92$ and RMSE < 19.1 kg).
- Body volume of the heifer is recommended as the most suitable predictor of live-weight.

ARTICLE INFO

Keywords:
Pasture-based
Dairy
Heifers
Live-weight
Linear body measurements

ABSTRACT

Monitoring the live-weight of dairy heifers and thus meeting weight-for-age targets is regarded as one of the most important aspects of a heifer rearing enterprise as it optimizes future production. This is particularly important in pasture-based heifer rearing systems where growth is non-linear due to seasonal variation in grass growth and quality. Data were collected throughout the rearing period to estimate the live-weight of pasture-based Holstein-Friesian (n = 130) and Jersey (n = 57) dairy heifers using linear body measurements. Live-weight was regressed on heart girth, body volume and a polynomial of body length, heart girth, and withers height; all equations were validated within-herd. All three equations were accurate predictors of live-weight for pasture-based dairy heifers ($R^2 > 0.92$ and RMSE < 19.1 kg), therefore, in the absence of weighing scales, live-weight can be successfully predicted using linear body measurements. The equation which utilizes body volume of the heifer is proposed as the most suitable predictor of live-weight.

1. Introduction

Live-weight has a greater effect on the attainment of puberty in pasture-based dairy heifers than that of age (Archbold et al., 2012). Therefore, achieving weight-for-age targets (Troccon, 1993) will ensure heifers have achieved puberty prior to breeding at 15 months, which is essential to maintain a compact calving pattern. Electronic scales are widely used for monitoring the growth of animal's worldwide (Lukuyu et al., 2016). However, the uptake of technology among Irish and New Zealand farmers is particularly low (Teagasc, 2016; McNaughton and Lopdell, 2012). In New Zealand, less than 5% of heifers had a live-weight recorded prior to calving (McNaughton and Lopdell, 2012); while in Ireland, there were no figures available. It is evident; therefore, that the weighing of heifers is infrequent, and as such, farmers may be reluctant to invest in an electronic weighing scale.

In the absence of an electronic weighing scale, linear body measurements (LBM) such as heart girth (HG), withers height (WH), and body length (BL; Lukuyu et al., 2016) may be relatively accurate in their prediction of live-weight (Heinrichs et al., 1992) and are inexpensive to undertake. Previous research on the use of LBM to predict live-weight has been undertaken in confinement heifer rearing systems where the growth trajectory is linear (Heinrich et al., 1992). However, in pasture-based systems, such as Ireland, grass growth and quality are highly variable (Hennessy et al., 2020) and consequently, heifer growth is non-linear (Handcock et al., 2019). The relationship between LBM and live-weight varies with breed (Reis et al., 2008). Therefore, different

* Corresponding author.
E-mail address: emer.kennedy@teagasc.ie (E. Kennedy).

https://doi.org/10.1016/j.livsci.2021.104693
Received 18 December 2020; Received in revised form 27 August 2021; Accepted 30 August 2021
Available online 2 September 2021

prediction equations may be required for pasture-based heifers of contrasting breed groups, such as Holstein-Friesian (HF) and Jersey (JE; Handcock et al., 2019). The objective of the present study therefore was to devise a series of equations to predict live-weight from LBM of different breed groups of pasture-based dairy heifers from birth to 15 months. This will be beneficial for pasture-based dairy farmers as it allows them to monitor the growth of heifers, in the absence of a weighing scale.

2. Materials and methods

The present data were collected from heifers reared on the Dairygold Research Farm at Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Kilworth, Co. Cork, Ireland (52°09′N 8°16′W) between February 2018 and September 2020. In brief, a 2 (weaning ages; eight or 12 weeks) x 2 (post-weaning planes of nutrition; high (H) or low (L)) factorial design was in place. There were 187 heifer calves born in 2018 (n = 62 HF heifers and n = 26 JE with mean birth live-weights of 34.4 ± 4.67 kg and 23.0 ± 2.38 kg, respectively) and 2019 (n = 68 HF and n = 31 JE heifers with mean birth live-weights of 35.2 ± 4.23 kg and 24.5 ± 2.88 kg, respectively) assigned to the study.

All calves received 3 L colostrum within two hours of birth, followed by five feeds of transition milk. Calves were then grouped by age until they reached their respective weaning ages. When grouped, they were offered 6 L/day 26% crude protein milk replacer, *ad-libitum* fresh clean drinking water, concentrates and straw.

Following weaning, calves were regrouped according to their post-weaning treatment (H or L) and rotationally grazed perennial ryegrass dominated swards until housing the following winter. During the first grazing season, the H heifers were offered 1.5 kg of concentrate/heifer/day; however, if grass quality and availability were poor, the quantity of concentrate offered increased to 2.5 kg concentrate/heifer/day. Similarly, the L heifers were offered 0.5 kg of concentrate/heifer/day; however, if grass quality and availability were poor, the concentrates offered were increased to 1.5 kg concentrate/heifer/day. A difference in concentrate offered was maintained between the H and L heifers at all times. Over-winter management was similar for treatments; from week one to three, and again during weeks nine to 15, heifers grazed a forage crop (Redstart) *in-situ*, in addition to *ad-libitum* hay and 1 kg concentrates/heifer/day. During weeks four to eight of the over-winter period, heifers were housed and offered grass silage and 1.5-2 kg concentrate/heifer/day, depending on silage quality. At turnout to grass for their second grazing season, heifers were re-grouped by post-weaning treatment (H or L) and offered an all-grass diet. Contrasting pasture allowances were offered to create differences between the treatments; post-grazing heights of 4.5 and 3.5 cm were targeted for H and L heifers, respectively. The live-weights, average daily gain (ADG) between weigh dates, and LBM throughout the experimental period are outlined in Table 1.

Live-weight (kg; TruTest XR 3000, Tru-test Limited, Auckland, New Zealand) and LBM (cm) data were recorded twice a month from birth until nine months and every three months thereafter until breeding at 15 months. A soft measuring tape was used to measure the BL (horizontal distance from the top of the withers to the ischium) and HG (circumference of the animal's body measured directly behind the front legs). A specialised measuring stick (Nasco, Fort Atkinson, WI) was used to measure the WH (vertical distance from the ground to the top of the withers).

2.1. Statistical analysis

Statistical analyses were conducted using SAS (version 9.4; SAS Institute Inc., Cary, NC). Regressions of live-weight on LBM were tested (PROC REG) across the entire dataset, and then for HF and JE separately. Stratifying the dataset by breed group was found to increase the accuracy of prediction, therefore verifying that separate comprehensive equations were required for pasture-based HF and JE heifers as growth was non-linear (Table 1 and Fig. 1). Regressions of live-weight on HG, WH, BL and their combinations were tested (PROC REG) prior to cross-validation, which aimed to validate a series of the best parameters. Three equations were selected for cross-validation such that equations that utilized one, two and three LBM, respectively, were created. Within-herd validation involved stratifying the HF and JE datasets by birth year, pre- and post-weaning treatment. Numerical differences between the HF and JE datasets resulted in an average of 25% and 33%, respectively, of records from each stratum being removed for validation. The remaining records from each stratum were used to create the equations: heifers were not present in the calibration and validation data sets simultaneously. This process was repeated four and three times for HF and JE datasets, respectively, until all records had been tested using within-herd validation once. Regressions of live-weight on HG, WH, BL and their polynomial combinations were then performed. Body volume (BV) of the heifer was also regressed on live-weight whereby BV was calculated using the formula to calculate cylinder volume:

Table 1
Data available for regression analysis of HF and JE dairy heifers.

	HF (n = 130)		JE (n = 57)	
	μ	SD	μ	SD
3 months				
Weight	87.3	11.47	68.1	10.60
ADG birth to 3 months	0.63	0.133	0.53	0.124
Length	75.9	4.78	71.1	6.199
Girth	108.0	5.94	99.0	7.892
Height	89.8	3.39	83.7	4.37
6 months				
Weight	148.9	18.57	113.5	13.25
ADG 3 to 6 months	0.73	0.165	0.55	0.145
Length	84.8	3.48	80.8	4.50
Girth	127.4	7.99	118.5	8.08
Height	100.4	4.22	93.3	3.08
9 months				
Weight	215.7	25.29	168.1	18.83
ADG 6 to 9 months	0.80	0.182	0.65	0.194
Length	97.4	3.44	92.9	3.39
Girth	145.4	6.76	136.2	5.89
Height	109.6	4.05	105.0	3.00
12 months				
Weight	253.9	28.50	200.0	18.63
ADG 9 to 12 months	0.45	0.135	0.38	0.150
Length	105.4	3.59	102.5	3.08
Girth	156.5	7.47	148.2	6.73
Height	115.9	4.43	109.9	3.31
15 months				
Weight	304.4	28.76	238.8	20.71
ADG 12 to 15 months	0.60	0.130	0.46	0.127
Length	110.0	3.45	107.5	3.19
Girth	166.2	6.41	157.0	5.76
Height	120.1	4.33	114.5	3.09

[1]ADG = average daily gain.

$$Body\ volume = \pi r^2 h$$

where π = 3.14, r = (HG/2 π) and h = BL. Both linear and non-linear relationships were tested. All regression equations then underwent within-herd validation. The association between predicted and actual live-weight was assessed using regression analysis.

The statistical methodology used to evaluate the accuracy of live-weight predicted by the model compared with actual live-weight on 25% and 33% of the data for the HF and JE heifers, respectively, was similar to that of Ruelle et al. (2019). In brief, the R^2, root mean square error (RMSE), slope of the line, mean square prediction error (MSPE), relative prediction error (RPE), and concordance correlation coefficient (CCC) were used to determine if the model accurately predicted live-weight. The MSPE is the sum of three components: mean bias $(M_m - P_m)^2$, line variation $S^2_p\,(1 - b)^2$, and random variation about the line, $S^2_m\,(1 - R^2)$, whereby each is expressed as a proportion of the total MSPE:

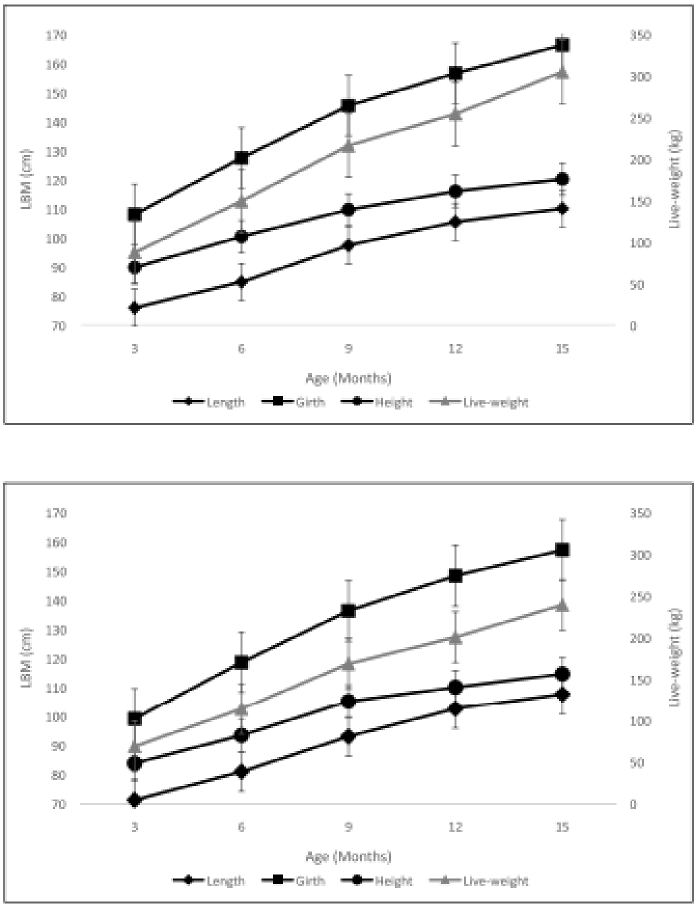


Fig. 1. Live-weights, lengths, girths and heights of Holstein-Friesian (HF) and Jersey (JE) heifers.

$$MSPE = \frac{\sum(M-P)^2}{n} = (M_m - P_m)^2 + S_p^2(1-b)^2 + S_m^2(1-R^2)$$

where *n* is number of records, *M* and *P* are measured and predicted live-weights, respectively, *Mm* and *Pm* are mean values of *M* and *P*, respectively, S_m^2 and S_P^2 are variances of M and P, respectively, b is the slope of the line of P regressed on M; and R^2 is the coefficient of determination of the line. The root mean square prediction error (RMSPE) is the root of the MSPE. The RPE is calculated as:

$$RPE = \left(\frac{RMSPE}{M_m}\right) \times 100$$

The CCC is comprised of two components:

$$CCC = p \times Cb$$

where *p* is the Pearson correlation coefficient and *Cb* is the bias correction factor:

$$Cb = \frac{2 \times \sigma_m \times \sigma_p}{\sigma_m^2 + \sigma_p^2 + (\mu_m - \mu_p)^2}$$

and σ_m, σ_p, μ_m and μ_p are the standard deviation and average of the measured and predicted data, respectively. The CCC evaluates the correlation between the actual and predicted live-weights but also the deviation from the 45° line.

3. Results

The fitting statistics for the equations are outlined in Table 2 whereby values reported are the average of the four and three iterations for the HF and JE within-herd validations, respectively.

All three equations accurately predicted live-weight (Fig. 2) with RPE values of between 8.1 and 12.5%. In all equations, a high proportion of MSPE (>97.4%) was attributable to random variation. The equations to predict live-weight had average R^2 and RMSE values of 0.95 (range 0.92 – 0.97) and 14.8 kg (range 11.8 – 19.1 kg), respectively. Although still an extremely good predictor of live-weight for HF and JE heifers (RPE 11.5 and 12.5, respectively), the equation that predicted live-weight using a single LBM, namely HG, resulted in inferior fitting statistics compared to the equation that utilized two and three LBM. Including all three LBM as a polynomial in the prediction equation improved RPE values by 3.4 and 3.6% for HF and JE heifers, respectively, compared to the equation that utilized one LBM. The equation that regressed live-weight on BV was also found to accurately predict

Table 2
Comparison between the actual and predicted live-weight (kg) of HF (A) and JE (B) heifers for the different simulations using within herd validation, respectively.

(A)					Proportion of the MSPE					
	Measured	**Predicted**	**Slope**	**RMSPE**	**Mean**	**Line**	**Random**	**RPE**	**CCC**	**C bias**
Girth	166. 5	166.6	1.00	19.1	0.3	0.1	99.6	11.5	0.97	1.00
Body volume [1]	166. 5	166.6	1.00	15.0	0.1	0.6	99.4	9.0	0.98	1.00
Length, Girth, Height, Length², Girth² and Height²	166.4	166.4	1.00	13.5	0.5	0.5	99.0	8.1	0.98	1.00
(B)					Proportion of the MSPE					
	Measured	**Predicted**	**Slope**	**RMSPE**	**Mean**	**Line**	**Random**	**RPE**	**CCC**	**C bias**
Girth	130.6	130.6	1.00	16.3	0.6	0.4	99.0	12.5	0.96	1.00
Body volume[1]	130.6	130.6	1.00	13.5	1.8	0.8	97.4	10.3	0.97	1.00
Length, Girth, Height, Length², Girth² and Height²	130.6	130.5	1.00	11.7	0.2	0.1	99.8	8.9	0.98	1.00

[1] Body volume was regressed on live-weight whereby the formula to calculate cylinder volume was utilized
[2] RMSPE – root mean square prediction error; MSPE – mean square prediction error; RPE – relative predicted error; CCC – concordance correlation coefficient; Cbias – bias of the concordance correlation coefficient

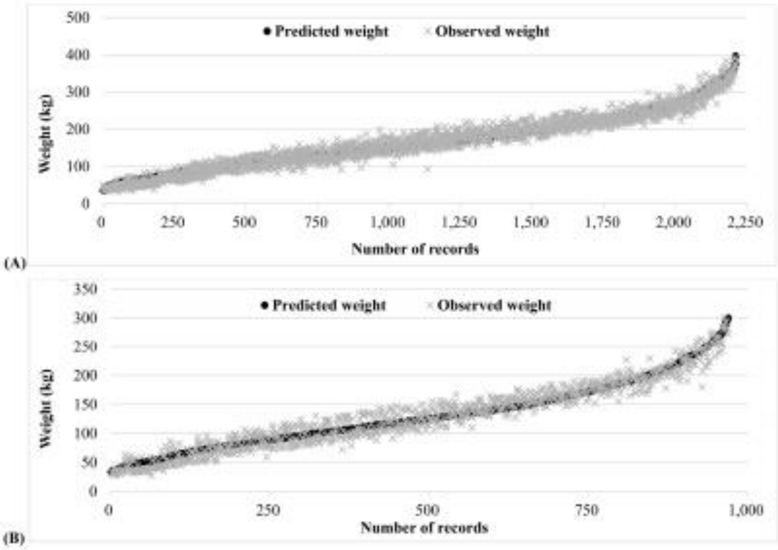


Fig. 2. Comparison between observed live-weight (x) and predicted live-weight (●) of Holstein-Friesian (A) and Jersey (B) heifers.

live-weight, with RPE values of 9.0 and 10.3% for HF and JE heifers, respectively. The regression equations used to predict live-weight for HF and JE heifers are presented in Table 3.

Table 3
Regression equations created using the lengths (L), girths (G), heights (H) and body volumes (BV) of HF (A) and JE (B) heifers, respectively.

(A)	**Equation**	**R²**	**RMSE**
Girth	-235.2 + 3.2 (G)	0.93	19.13
Body volume	8.3 + 0.0012 (BV)	0.96	15.06
Length, Girth, Height, Length², Girth² and Height²	-89.2 - 3.3 (L) -1.2 (G) + 4.3 (H) + 0.027 (L²) + 0.010 (G²) + 0.009 (H²)	0.97	13.23
(B)	**Equation**	**R²**	**RMSE**
Girth	-198.6 + 2.7 (G)	0.92	16.31
Body volume	7.1 + 0.0011 (BV)	0.95	13.37
Length, Girth, Height, Length², Girth² and Height²	-7.5 - 3.4 (L) + 0.1 (G) + 1.4 (H) + 0.0028 (L²) + 0.004 (G²) + 0.003 (H²)	0.96	11.79

[1]RMSE – root mean square error

4. Discussion

The aim of the present study was to develop equations to predict live-weight of growing dairy heifers in a pasture-based system. Equations have been developed previously (Heinrichs et al., 1992), however, these animals were reared in confinement heifer rearing systems where precision nutrition ensures greater efficiency of nutrient utilization (Zanton and Heinrichs, 2008). In pasture-based heifer rearing systems, such as that in Ireland, heifers are offered a predominately grazed-grass diet, with concentrate supplementation when grass growth and quality are poor. Consequently, heifers reared in pasture-based systems follow a seasonal pattern of growth (Handcock et al., 2019). Similar to Heinrichs et al. (1992) HG was highly correlated ($R^2 > 0.92$ and RPE 11.5 and 12.5% for HF and JE, respectively) with live-weight, and was therefore used to develop a simple equation for the prediction of live-weight. The use of a single LBM to predict live-weight may be useful for farmers who wish to monitor growth of their heifers but may not have time to measure several dimensions of skeletal growth. The inclusion of two or more LBM in the regression equation slightly improved live-weight prediction: the regression equation for BV utilized HG and BL and was found to predict HF and JE heifer live-weight to within 13.4 and 15.1 kg of live-weight, respectively. Body volume was previously found to be highly correlated with live-weight of native Indonesian cows (Paputungan et al., 2015), however, to the best of the authors knowledge, BV has never been used to predict live-weight of pasture-based heifers. Similar to Reis et al. (2008), including three independent LBM in the equation increased prediction accuracy. Furthermore, polynomial regression of BL, HG and WH on live-weight improved the fit statistics further with an R^2 of 0.97 and 0.96 and RMSE of 13.2 and 11.8 kg for HF and JE heifers, respectively. However, the polynomial regression equation was only marginally better than the BV equation, therefore, from a practicality perspective, the BV equation is more appropriate for a labor-intensive dairy farm.

5. Conclusion

The equations developed in this study are all highly effective in their prediction of live-weight of pasture-based HF and JE dairy heifers. The equation, which utilizes BV of the heifer, is proposed as the most suitable predictor of live-weight. Despite utilizing just two LBM, it displays a high accuracy of prediction and will enable dairy farmers to monitor the growth of their heifers in the absence of a weighing scale.

Author Statement

All authors have seen and approved the final version of the manuscript being submitted. This article is the authors' original work, has not received prior publication and is not under consideration for publication elsewhere.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgements

The authors would like to acknowledge the support of the Department of Agriculture, Food, and the Marine for their funding (MultiRepro project (15/S/696)). We also thank the staff at the Dairygold Research Farm for their care of the animals and their help with data collection.

References

Archbold, H., Buckley, F., Pierce, K.M., Begley, N., Mee, J.F., 2012. Ultrasonography and progesterone concentration at a single time point for the detection of puberty in dairy heifers. Reprod. Domest. Anim. 47 (3), 407–411.

Handcock, R.C., Lopez-Villalobos, N., McNaughton, L.R., Back, P.J., Edwards, G.R., Hickson, R.E., 2019. Live weight and growth of Holstein-Friesian, Jersey and crossbred dairy heifers in New Zealand. N.Z. J. Agric. Res. 62 (2), 173–183.

Heinrichs, A. J., G. Rogers, and J. Cooper. 1992. Predicting body weight and wither height in Holstein heifers using body measurements. 75(12):3576-3581.

Hennessy, D., Delaby, L., van den Pol-van Dasselaar, A., Shalloo, L., 2020. Increasing grazing in dairy cow milk production systems in Europe. Sustainability 12 (6), 2443.

Lukuyu, M.N., Gibson, J.P., Savage, D.B., Duncan, A.J., Mujibi, F.D.N., Okeyo, A.M., 2016. Use of body linear measurements to estimate liveweight of crossbred dairy cattle in smallholder farms in Kenya. SpringerPlus 5 (1), 63.

McNaughton, L., Lopdell, T., 2012. Brief communication: are dairy heifers achieving live weight targets?. In: Proceedings of the New Zealand Society of Animal Production, pp. 120–122.

Paputungan, U., Hakim, L., Ciptadi, G., Lapian, H.F.N., 2015. Application of body volume formula for predicting live weight in Ongole crossbred cows. International Journal of Livestock Production 6 (3), 35–40. In this issue.

Reis, G.L., Albuquerque, F.H.M.A.R., Valente, B.D., Martins, G.A., Teodoro, R.L., Ferreira, M.B.D., Monteiro, J.B.N., Silva, M.d.A., Madalena, F.E., 2008. Prediction of live weight based on body measurements in crossbred animals Holstein/Gir. Ciênc. Rural 38 (3), 778–783.

Ruelle, E., Delaby, L., Shalloo, L., 2019. Linkage between predictive transmitting ability of a genetic index, potential milk production, and a dynamic model. J. Dairy Sci. 102 (4), 3512–3522.

Teagasc, 2016. Teagasc Technology Foresight: Technology Transforming Irish Agri-Food and Bio-Economy. Teagasc Agriculture and Food Development Authority, Carlow, Ireland.

Troccon, J., 1993. Effects of winter feeding during the rearing period on performance and longevity in dairy cattle. Livest. Prod. Sci. 36 (2), 157–176.

Zanton, G., Heinrichs, J., 2008. Precision feeding dairy heifers: strategies and recommendations. College Agric. Sci.,, DAS:08-130.

10.2 Conference Proceedings

Costigan, H., Walsh, S. and Kennedy, E. (2019). 'Effect of weaning age on growth performance of dairy heifer calves'. In *The British Society of Animal Science Conference* Edinburgh, Scotland

Effect of weaning age on growth performance of dairy heifer calves

H. Costigan*†, S. Walsh†, E. Kennedy*
*Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland
†Waterford Institute of Technology, Cork Road, Waterford City, Co. Waterford, Ireland

Objective

To determine if Holstein Friesian (HF) and Jersey (JE) dairy heifer calves weaned at 12 weeks are heavier than those weaned at 8 weeks

Introduction

An early transition from milk to solid feed is considered an important economic objective for dairy farmers, however increased milk consumption as a result of delayed weaning can also benefit the production potential of the calf

Materials and Methods

- 98 JE and HF heifer calves randomised for breed (61 HF and 37 JE), birth weight (30.2 ± 6.90 kg) and birth date (10 February; ± 13.2 days)
- Fed 3 litres of (>22% Brix) colostrum at birth and 6 litres/day of transition milk in individual pens for 3 days
- Grouped by age from 3 days old and fed 6 litres/day of 26% crude protein milk replacer
- *Ad-libitum* fresh water, concentrate and straw offered in group pens




- Heifers were weighed twice a month (Tru-Test, Palmerston North, NZ)
- Weight gain calculated as the increase in live-weight between weigh dates
- Gradually weaned over 7 days at either 8 or 12 weeks old

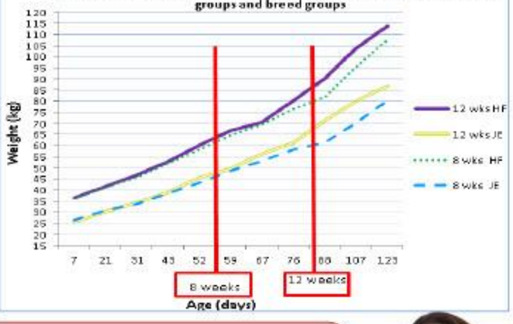
Results

- Weights were significantly different between late and early weaned calves in week 12; 8 week weaned calves were on average 71.6 kg and 12 week weaned calves were on average 80.6 kg
- Average daily gain for 8 and 12 week weaned calves in weeks 1-12 was 0.48 kg/day and 0.58 kg/day, respectively
- In week 13-16, 8 and 12 week weaned calves gained 0.50 and 0.47 kg/calf/day, respectively
- JE calves were consistently lighter than HF as a result of lower birth weights (JE 27.7 kg; HF 34.4 kg)

Table 1. Pre-weaning and post-weaning liveweight gains across weaning groups and breed groups

		WEIGHT				ADG			
		12 wks		8 wks		12 wks		8 wks	
		HF	JE	HF	JE	HF	JE	HF	JE
Week 1-8	7	36.6	25.5	36.3	26.4	0.33	0.34	0.30	0.52
	21	41.7	30.2	41.2	30.9	0.36	0.35	0.36	0.37
	31	46.7	34.2	45.8	33.7	0.51	0.39	0.48	0.32
	43	53.0	39.0	52.1	38.4	0.51	0.41	0.46	0.39
	52	60.1	45.8	58.3	43.1	0.82	0.79	0.76	0.58
	59	66.8	49.6	64.9	48.7	0.12	0.08	0.11	0.09
Weight 9-12	67	70.3	56.1	69.6	53.2	0.77	0.84	0.58	0.47
	76	80.2	61.3	76.4	58.3	0.87	0.53	0.97	0.63
	88	90.2	71.1	81.9	61.4	1.23	1.19	0.78	0.55
Week 13-16	107	103.5	79.7	95.2	70.2	0.62	0.42	0.59	0.28
	123	113.6	86.9	107.4	80.0	0.55	0.31	0.66	0.48

Figure 1. Pre-weaning and post-weaning liveweight gains across weaning groups and breed groups



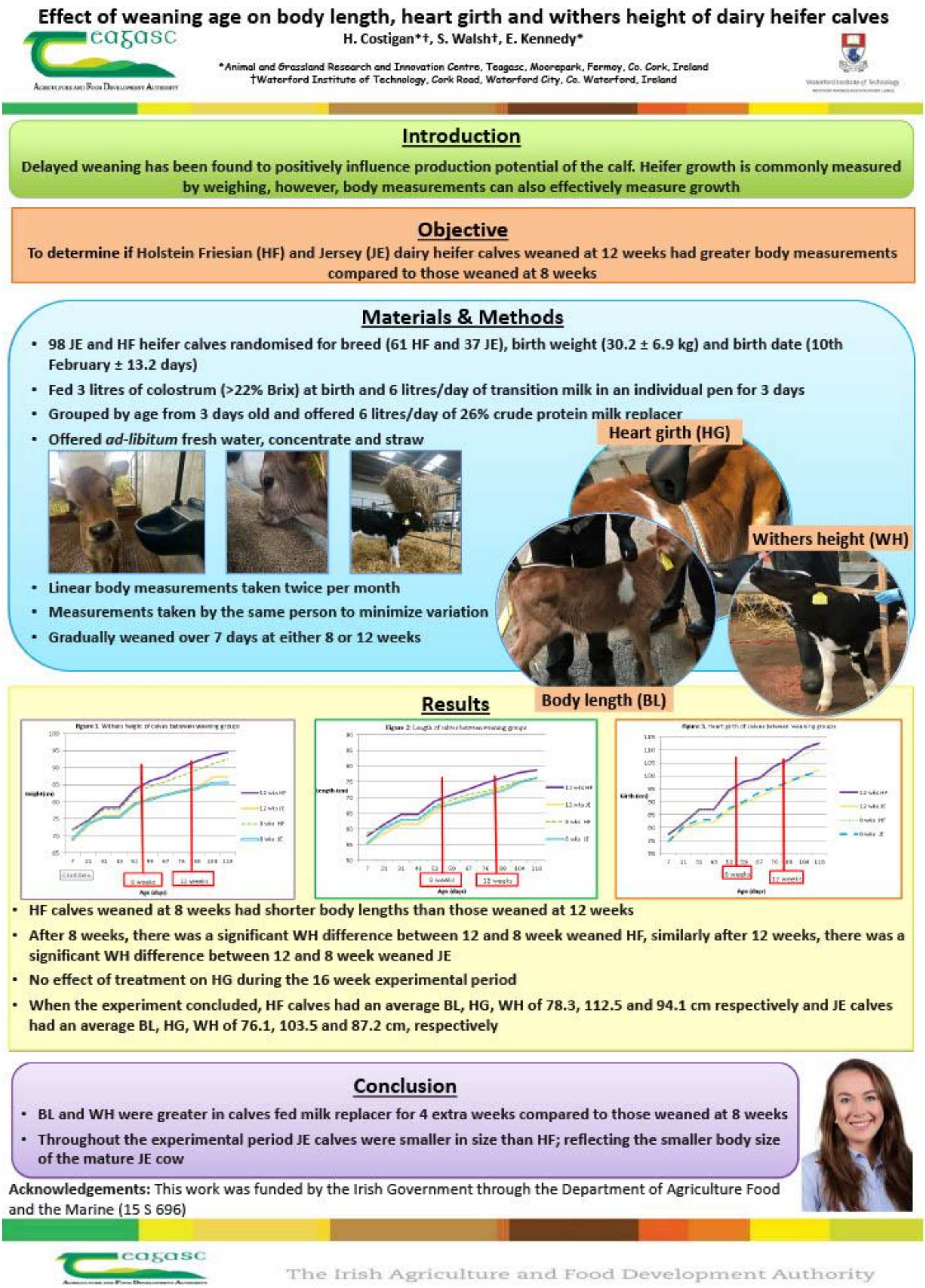
Conclusion

- No significant effect of treatment on liveweight up to week 8
- Additional milk replacer consumed by later weaned calves from week 8-12 resulted in a weight advantage
- In the post-weaning period (week 13-16) average daily gain was similar between treatments

Acknowledgements: This work was funded by the Irish Government through the Department of Agriculture Food and the Marine (15 S 696)

The Irish Agriculture and Food Development Authority

Costigan, H., Walsh, S. and Kennedy, E. (2019). 'Effect of weaning age on body length, heart girth and withers height of dairy heifer calves'. In *The British Society of Animal Science Conference* Edinburgh, Scotland



Costigan, H., Walsh, S. and Kennedy, E. (2019). 'Effect of weaning age on growth performance of dairy heifer calves' in Rural Futures II: Towards Sustainable Solutions for Ruminant Pastoral Agricultural Systems in Scotland and Ireland Ashtown Food Research Centre, Dublin

Effect of weaning age on growth performance of dairy heifer calves

H. Costigan*†, S. Walsh†, E. Kennedy*

*Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland
†Waterford Institute of Technology, Cork Road, Waterford City, Co. Waterford, Ireland

Objective

The objective of the present research was to determine if weaning age had an effect on live-weight, body length (BL), heart girth (HG) and withers height (WH) of Holstein-Friesian (HF) and Jersey (JE) dairy heifer calves

Introduction

An early transition from milk to solid feed is considered an important economic objective for dairy farmers, however increased milk consumption as a result of delayed weaning can also benefit the production potential of the heifer when she calves and starts producing milk

Materials and Methods

- 98 heifer calves were balanced for breed (61 HF + 37 JE), birth-weight (30.2 ± 6.90 kg) and date of birth (10 February; ± 13.2 days)
- Fed 3 litres of colostrum at birth; 6 litres/day of transition milk in individual pen for 3 days
- Grouped by age from 3 days old and fed 6 litres/day of 26% crude protein milk replacer
- *Ad-libitum* fresh water, concentrate and straw offered
- Gradually weaned over 7 days at either 8 or 12 weeks old
- Heifers were weighed (Tru-Test, Palmerston North, NZ) and linear measurements were taken twice a month

Results

- Weights were significantly different between 8 and 12 weaned calves in week 12
- At 12 weeks of age the BL, HG and WH were significantly higher for the 12 week compared to 8 week weaned calves
- JE calves were consistently lighter and smaller than HF as a result of lower birth weights (JE 27.7 kg; HF 34.4 kg) and linear body measurements at birth

Figure 1. (a) Body length, (b) Heart girth and (c) Withers height across weaning and breed groups

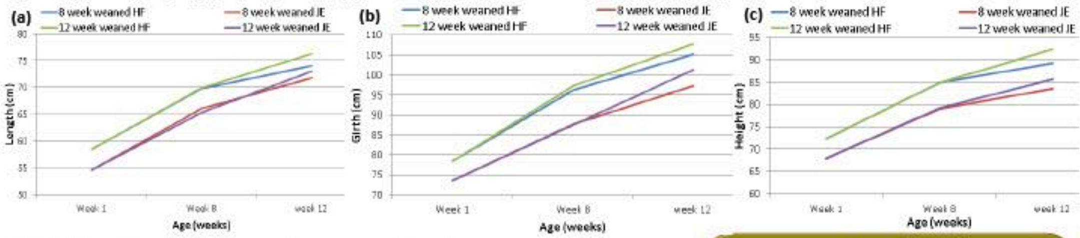


Table 1. Liveweight gains across weaning groups and breed groups

	Group		P- value	Breed		P-value	SE
	8 weeks	12 weeks	Treatment	HF	JE	Breed	
Weight (kg)							
Week 8	56.7	57.8	0.8116	65.6	48.9	<0.0001	1.11
Week 12	72.7	79.3	0.0094	87	65	<0.0001	1.64
Weight gain (kg/day)							
birth-8wks	0.47	0.49	0.8445	0.52	0.44	0.0018	0.02
birth-12wks	0.51	0.59	0.0055	0.61	0.49	<0.0001	0.02
8-12weeks	0.62	0.81	<.0001	0.8	0.63	0.0001	0.03

Conclusion

- No significant effect of treatment on liveweight up to week 8
- Additional milk replacer consumed by later weaned calves from week 8-12 resulted in a weight and size advantage
- Heifers will be monitored until they enter the milking herd at 24 months

Acknowledgements: This work was funded by the Irish Government through the Department of Agriculture Food and the Marine (15 S 696)

The Irish Agriculture and Food Development Authority

10.3 Technical Publications

Costigan, H., Fitzgerald, R., Hennessy, W., and Kennedy, E. (2019). 'Do weaning age and post-weaning growth rate have an effect on replacement heifers achieving target weight?' In *Irish dairying – growing sustainably*. Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork

IRISH DAIRYING | GROWING SUSTAINABLY

Do weaning age and post-weaning growth rate have an effect on replacement heifers achieving target weight?

Hazel Costigan, Ricki Fitzgerald, William Hennessy and Emer Kennedy
Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork

Summary

- At 12 weeks, 12 week weaned calves were heavier than eight week weaned calves as a result of the additional milk replacer consumed.
- Data from year one of the study showed some compensatory growth when heifers were turned out for their second season at grass.

Introduction

Replacement heifers represent the future potential of the dairy herd. However, the cost of rearing a replacement heifer is high at €1,545; in addition calf rearing is one of the most labour-intensive tasks on a dairy farm so can also incur extra costs associated with additional labour. Weaning calves at an earlier age (e.g. 8-weeks) compared to delayed weaning (e.g. 12-weeks) and feeding a higher quantity of concentrate post-weaning could help overcome the demand for additional labour and contribute to reducing costs associated with rearing a replacement heifer. However, to ensure heifers realise their potential in the lactating herd they need to achieve target weights at specified time points in the first two years of life (Table 1).

Table 1. Bodyweight (Kg) targets for heifers at six months, breeding and pre-calving (HF = Holstein-Friesian, JE= Jersey)

	HF	JE	HF*JE
3 month old	115	80	100
10 month old	250	175	215
Pre-breeding	330	240	295
Pre-calving	550	405	490

Study

In spring 2018 a three-year study commenced at Teagasc Moorepark to investigate the effect of weaning calves at either eight or 12 weeks of age. At birth, 98 heifer calves were divided into four treatment groups making sure they were equal for breed, birth weight, and birth date. The four treatments were i) weaned at eight weeks and offered a high level of concentrate post-weaning; ii) weaned at eight weeks and offered a low level of concentrate post-weaning iii) weaned at 12 weeks and offered a high level of concentrate post-weaning and iv) weaned at 12 weeks and offered a low level of concentrate post-weaning. It was expected that when weaned at 12-weeks of age calves would be heavier than those weaned at eight weeks, but the experiment aimed to investigate if weaning earlier (e.g. 8-weeks) and offering greater concentrate in the post-weaning period would result in similar weights at key time-points, such as at breeding.

Colostrum and transition milk management were the same for all calves; within an hour of birth heifers were fed three litres of good quality colostrum. Heifers were then fed six litres/heifer/day of transition milk for three days in an individual pen. Heifers were grouped

Page 168

from three days and fed 26% crude protein milk replacer at a rate of six litres/heifer/day using an automatic feeder (reconstitution rate 15%) until they were gradually weaned (over a week) off milk replacer at eight or 12 weeks old. *Ad-libitum* water, concentrate and straw were offered from three days old.

After weaning, heifers were managed in groups of 50. Heifers had full time access to pasture and were supplemented with 2.5 or 1.5 kg concentrate/heifer/day depending on their post-weaning feeding rate (high and low concentrate, respectively). Heifers in both the high and low post-weaning growth rate groups were fed a common diet of silage and concentrates over winter. At turnout in March, heifers previously on high and low concentrate were grazed to 4.5 cm and 3.5 cm post-grazing sward heights, respectively. Heifers were weighed twice a month until housing and once a month thereafter.

In the pre-weaning period, eight and 12 week weaned calves consumed 50.4 kg/calf and 75.6 kg/calf of milk replacer, respectively. Weight gain was not different between weaning groups up to week eight as calves were fed identical diets. From week 8–12, 12 week weaned calves gained on average 0.79 kg/day and eight week weaned calves gained on average 0.62 kg/day. As a result there was a 6.1 (± 1.81) kg weight difference between the eight and 12 week weaned calves at 12 weeks. This 6.1 kg weight difference remained until turnout in early February. However, by breeding at 15 months, 12 week weaned calves were only 3.2 kg heavier than eight week weaned calves (Figure 1).

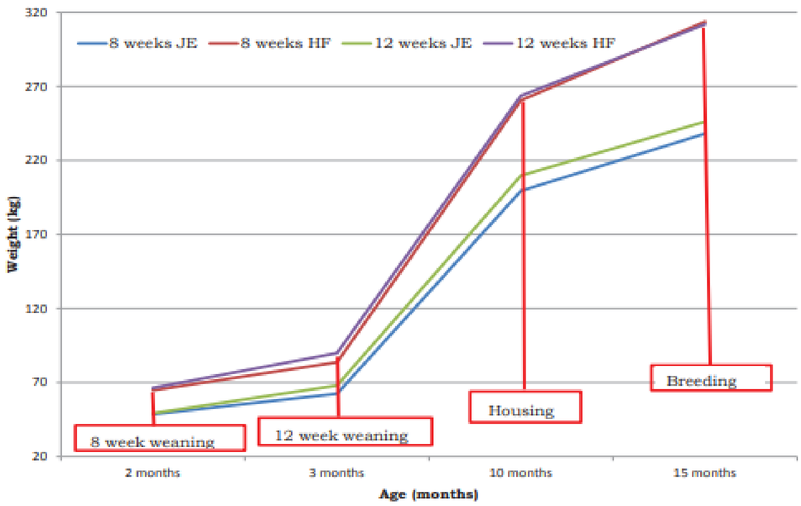


Figure 1. *Liveweight across weaning and breed groups*

Conclusions

At 12 weeks the eight and 12 week weaned calves were on average 72.4 and 78.5 kg, respectively. The weight difference between the eight and 12 week weaning groups had reduced to 3.2 kg by breeding at 15 months. However, this is only data from the first year of the experiment and data from the next two years needs to be collected and analysed before definite conclusions can be drawn.

Acknowledgements

This work was funded by the Irish Government through the Department of Agriculture Food and the Marine Research Stimulus Fund (15 S 696).

Costigan, H., Delaby, L., Fitzgerald, R., and Kennedy, E. (2021). 'The effect of different rearing strategies on heifer growth and the achievement of target weights' In *Irish dairying – delivering sustainability*. Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork

The effect of different rearing strategies on heifer growth and the achievement of target weights

Hazel Costigan[1], Luc Delaby[2], Ricki Fitzgerald[1] and Emer Kennedy[1]

[1]Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork; [2]INRA, Physiologie, Environnement, Génétique pour l'Animal et les Systèmes d'Elevage, 35590 St. Gilles, France

Summary

- Post-weaning feeding regime had a greater effect on body weight (BW) throughout the rearing period than weaning age
- At nine and 14 months, heifers should be approx. 40% and 50% of mature BW
- Meeting these targets will ensure heifers have achieved puberty prior to breeding when they should be approx. 60% of mature BW.

Introduction

Increasing the length of the milk-feeding period takes advantage of high feed efficiency in early life; however, it may not be economically viable. Alternatively, different feeding strategies post-weaning can ensure that BW targets, which are important key performance indicators in heifer rearing systems, are achieved. If heifers are 30%, 60% and 90% of mature BW (approx. 575 kg) at six, 15 (breeding) and 24 (pre-calving) months, respectively, they will have improved milk production, reproduction and survivability. However, these targets assume a linear growth trajectory, which is difficult in pasture-based rearing systems due to seasonal variation in grass growth and quality. Creating additional BW targets would be beneficial for pasture-based farmers to optimize heifer growth prior to breeding.

Study

A study took place at Teagasc Moorepark from February 2018 to November 2020. There were 177 Holstein-Friesian (mean birth BW of 34.6 ± 4.36 kg) heifers in the study. Experimental treatments are outlined in Figure 1. Heifers were weighed twice a month from birth until housing for the first winter and monthly thereafter.

Figure 1. *Schematic outline of the different weaning ages and post-weaning feeding regimes*

Results

The growth trajectories, from birth to calving, of the pasture-based heifers are outlined in Figure 2. The accelerating phase in early life corresponds to the high feed efficiency in the milk-feeding period. The curve then plateaus slightly during the first over-winter period. This lag is followed by exponential growth as the heifers are turned out to their second grazing season. All treatment groups achieved target BW at six months (30% of mature BW). However, with the exception of the group that received 12 weeks milk feeding and a high level of feeding post-weaning, all heifers were slightly behind target BW at 15 months. Irrespective of weaning age or post-weaning feeding regime, all heifers were ahead of target at 24 months (90% of mature BW). New weight-for-age targets, such as 40% of mature BW at approx. nine months of age, and 50% of mature BW at approx. 14 months of age, will help farmers better manage pasture-based heifer growth. With these targets, farmers can decide if concentrate supplementation is required during the over-winter period, or whether to allocate more grass to heifers after turnout.

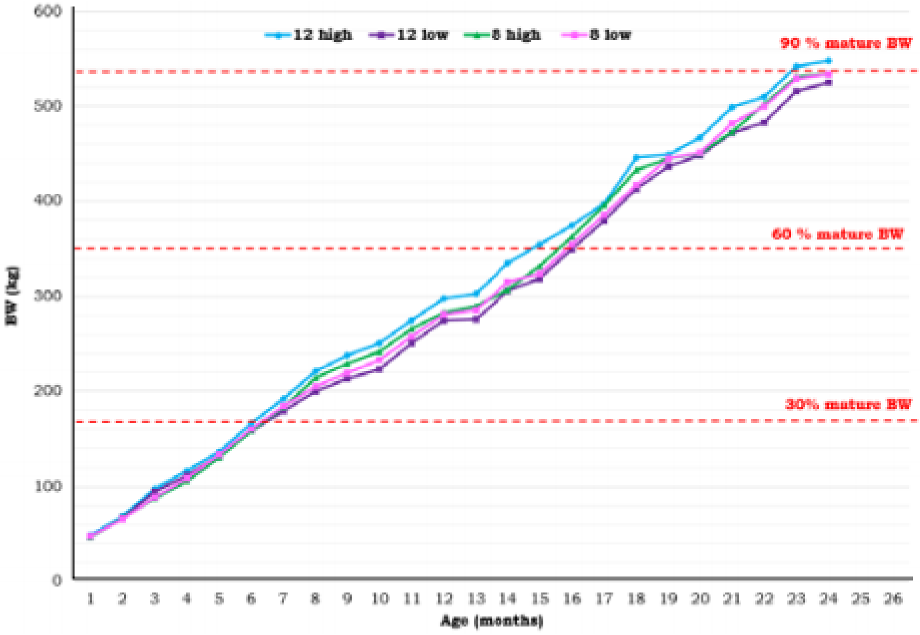


Figure 2. *The effect of weaning age and post-weaning feeding regime on body weight (BW) from birth until 24 months*

Conclusion

Post-weaning feeding had a greater effect than weaning age on BW from birth to calving. Heifers should be approx. 40% and 50% of mature BW (approx. 575 kg) at nine and 14 months, respectively, so that they have gained the BW necessary to achieve puberty before the breeding season. Having heifers ahead of target at calving may increase the risk of calving difficulty, therefore over-winter feed management should be optimized.

Acknowledgements

This work was funded by the Irish Government through the Department of Agriculture Food and the Marine Research Stimulus Fund (15 S 696).

Costigan, H., Galvin, N., Fitzgerald, R., and Kennedy, E. (2021). 'Heifer dry matter intake throughout the rearing period' In *Irish dairying – delivering sustainability*. Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork

Heifer dry matter intake throughout the rearing period

Hazel Costigan, Norann Galvin, Ricki Fitzgerald and Emer Kennedy
Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork

Summary

- Post-weaning feeding had a greater impact on dry matter intake (DMI) than weaning age
- DMI of pasture-based heifers was approximately 2.2% of body weight (BW) throughout the rearing period
- Jersey (JE) heifers had a higher intake as a percentage of BW compared to Holstein-Friesian (HF) heifers.

Introduction

Heifer DMI provides the foundation for BW gain and so is an important part of heifer rearing. Commonly expressed as a percentage of BW, DMI ranges from 1.8–2.9% throughout the rearing period. Previous heifer DMI research was undertaken in confinement rearing systems where feed of consistently good quality was offered year round. In pasture-based systems, such as those in Ireland, grass growth and quality are variable, and this may influence DMI. The objective of this research was to quantify the DMI of pasture-based heifers; this would benefit heifer management and grass allocation.

Study

Holstein-Friesian and JE heifers were weaned at either eight or 12 weeks, and offered either high (H) or low (L) feeding regimes post-weaning. In the first grazing season, H and L heifers were offered the same herbage allowance (4.5 kg/day) but different levels of concentrate (1.7 and 0.6 kg, respectively). In the second grazing season, post-grazing heights (5.1 and 3.7 cm, for H and L heifers respectively) were used to create differences in daily herbage allowance. A common diet of silage and concentrates was fed over-winter. The DMI of 60 heifers was determined on nine occasions throughout the rearing period (Table 1). Heifer body weight (BW) was monitored during each DMI estimation period.

Table 1. Ages, weights and dry matter intakes (DMI) of pasture-based Holstein-Friesian (HF) and Jersey (JE) heifers

Age (months)	Weight (kg)		Feed offered	DMI (kg/heifer per day)	
	HF	JE		HF	JE
6.8	174	129	Grass and concentrate	4.0	3.9
8.3	214	167	Grass and concentrate	4.2	4.3
9.0	212	157	Grass and concentrate	4.6	4.4
11.6	274	215	Silage and concentrate	5.3	4.7
13.8	287	225	Grass	6.0	5.5
17.4	395	310	Grass	7.7	7.3
17.4	408	321	Grass	8.1	7.5
19.5	466	369	Grass	9.8	8.9
19.9	449	359	Grass	10.1	9.1

Results

Heifer DMI is outlined in Table 1. Although almost all heifers achieved target BW at six and 24 months, the L heifers were slightly behind target at 15 months. Concentrate supplementation in the first grazing season had a greater effect on DMI than weaning age. Heifer DMI during the second grazing season was reduced from 8.3 kg to 7.7 kg when post-grazing height was reduced from 5.1–3.7 cm. Therefore, heifers behind target BW should not graze to low post-grazing heights, as it will slow their daily BW gain. Dry matter intake was similar for HF and JE in the first grazing season, in the second grazing season HF DMI was approximately 0.6 kg/day higher than JE (Figure 1). Although, DMI as a percent of BW decreased as BW increased, mean intake as a percentage of BW across the rearing period was 2.23% (2.53% and 2.09% for JE and HF, respectively).

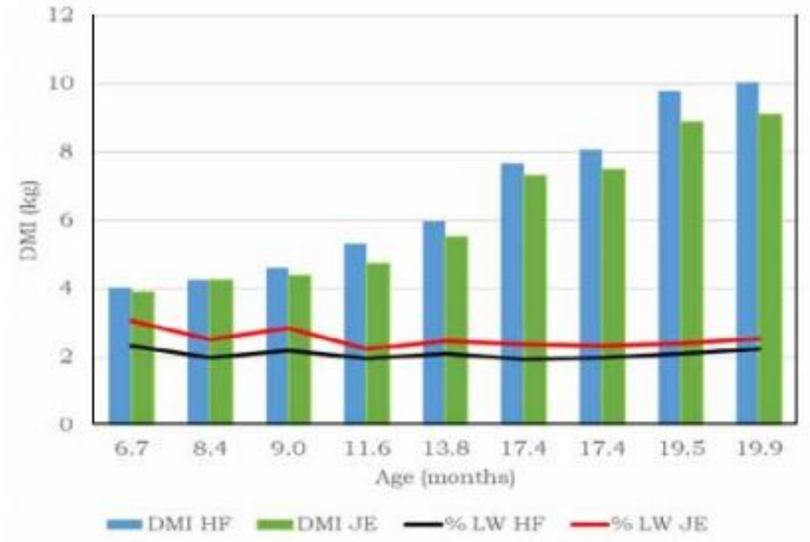


Figure 1. *The effect of breed on dry matter intake (DMI) and intake as a percentage of body weight (BW) of Holstein-Friesian (HF) and Jersey (JE) heifers*

Conclusion

Heifers weaned at 12 weeks and subsequently offered a high feeding regime had superior DMI, and therefore BW, throughout the rearing period. When DMI was expressed as a percentage of BW, JE had higher DMI than HF. High DMI from grass is essential to keep heifer rearing costs down. Lighter heifers should graze to approximately 5 cm post grazing sward heights so that live weight gain is not negatively impacted.

Acknowledgements

This work was funded by the Irish Government through the Department of Agriculture Food and the Marine Research Stimulus Fund (15 S 696).

10.4 Magazines/Podcasts

Irish Farm Business Magazine (Summer 2020 Edition). Keeping your Replacement Heifers on Target this Rearing Cycle. Emer Kennedy and Hazel Costigan. Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork

Heifer Management

Keeping your Replacement Heifers on Target this Rearing Cycle

by Emer Kennedy and Hazel Costigan

Rearing replacement heifers is a substantial investment on any dairy farm. It costs €1,545 to rear one replacement heifer from birth to calving at 24 months of age, and it takes 1.63 lactations for the heifer to pay off the investment before she starts returning a profit. If a heifer calves later than 26 months of age this substantially increases the cost associated with rearing and the return on investment is delayed as a result. Thus, the aim of rearing replacement heifers is very clear: get the heifers to calve at 24-months of age and achieve weight targets throughout the first two years of their life to maximise their production potential when they calve down and join the lactating herd. However, recent ICBF statistics show that over the last three years only 68 – 70% of replacement dairy heifers are calving between 22 and 26 months of age. This indicates that there is room for improvement in heifer rearing systems and that costs associated with rearing can be reduced by getting them to calve at the correct age. Achieving this starts from the day the calf is born.

During the first two years of the replacement heifer's life there are a series of target weights which need to be achieved. This helps to ensure that growth rate is consistent and that heifers reach the correct weight at breeding and at calving.

The key target weights to achieve at different time points are:

- 30% mature BW @ 6 months of age
- 60% mature BW @ 15 months of age or mating start date
- 90% mature BW pre-calving (~24 months of age)

Identifying mature weight of the herd

The first thing to do is identify the mature weight of your herd. Target weights are specific to your herd as the composition of everyone's herd is slightly different so it is important that you know your herds mature weight so that you can calculate target weights for your replacement heifers. The months of May and June are the ideal time to identify the mature weight of your spring-calving herd. At this time cows have recovered from their last pregnancy and if they are pregnant again, the foetus will not account for any additional weight at this stage. Identifying the mature weight of your herd is completed by weighting a sample of mature, well grown cows from the herd. Cows which are in their 3rd or greater lactation should be used as they are fully grown. The cows that you weigh should also represent the future of your herd i.e. what you want your future herd to look like. For example: if you are changing cow type, e.g. moving to Holstein Friesian x Jersey cross, base your target weights/ mature weight on Holstein Friesian x Jersey cross animals rather than Holstein-Friesians. Similarly, if you have animals which have had setbacks during the rearing period and as a result are not well-grown, do not use these animals to calculate your mature herd weight.

48 Farm Business

Importance of achieving target weight
Achieving target weights at each of the time points outlined above has previously been shown to maximise milk production potential and ensure longevity within the lactating herd. However, this comes with a word of caution. Replacement heifers which are ahead of target weight are at higher risk of having reduced longevity within the lactating herd. Teagasc Moorepark data has shown that heifers that were overweight at mating start date had a later calving date from second lactation onwards and a fewer number of total lactations than those heifers that were at target weight at mating start date. Having heifers ahead of target results in unnecessary expense as additional feed has been used to put the extra weight on the animals, and as the heifers do not remain in the herd for as long as those that achieved target weight it results in a higher replacement rate and a greater number of heifers need to be reared.

How to achieve target weight
At this stage of the year all replacement heifer calves should be weaned and grazing grass. At Teagasc Moorepark calves are offered pre-grazing yields of 1300 – 1400 kg DM/ha (similar to swards offered to lactating cows) and graze these swards to ~4cm post-grazing height. Fresh grass is offered every 2 – 3 days. Concentrate supplementation depends on grass availability and heifer weights. Calves are weighed regularly (every month) and are grazed in two separate herds according to their weight. The calves within these herds constantly change as one herd is for lighter calves and the other herd is for heavier calves. The aim is to try and obtain as uniform a herd as possible – the target weights are individual animal targets, not a herd average as within an average there can be a large range and ideally the range should be minimised.

The herd which contains the lighter calves always has less calves so there is reduced competition within the group. These calves are given preferential treatment – they get higher quality grass and more concentrate if necessary. At each weighing a minimum weight is set, calves over this weight go into the larger group with the heavier calves and calves below the weight go into the smaller group. It often happens that calves only need a short time in the lighter group before they move back to the heavier group.

The next target which we are currently working towards with the calves is to achieve 30% of mature bodyweight at six months of age. For example:

- 42 Holstein Friesian calves
- Mature weight of herd: 550 kg
- Weight on June 14th: 125 kg (range 105 – 145 kg)
- Target weight on Aug 5th (6 months old): 165 kg
- Need to gain 40 kg between June 14th and August 5th
- Daily weight gain: 52 days ÷ 40 kg = 0.78 kg/day

Using the example above achieving a weight gain of 0.78 kg/day should be achievable from a high quality grass diet, however continuous monitoring of calf weight is required as concentrate supplementation may be required if grass quality declines. Similarly, climatic conditions could have an effect on weight gain. Regular weighing will determine if concentrate supplementation is required to achieve target weights.

This management strategy should be continued for the remainder of the first grazing season. In addition to monitoring weight gain, a dosing regimen, which does not contribute to anthelminthic resistance, needs to be devised with your vet and herd vaccination protocols should also be adhered to.

Managing heifers during their second grazing season
Regardless of diet offered over the winter, weight gains achieved post-turnout are higher than those achieved during the winter. Heifers should be turned out to grass as soon as possible in spring, as they can gain up to 1 kg/day at grass compared to <0.70 kg/day while on their winter diet. Consequently heifers have a greater chance of attaining their target weight with early turnout.

During the main grazing season heifers should graze covers of 1400 – 1500 kg DM/ha and achieve a post-grazing height of 4cm, this will train them for efficient grazing when they join the lactating herd. While a number of people use leader follower systems, i.e. the younger calves graze ahead of the older heifers, which is beneficial for parasite control, caution should be exercised as both groups of animals are growing and require sufficient nutrients to attain their target weights. If the group of in-calf heifers are below target weight they should not be grazed in a leader follower system.

An exercise similar to the one above should be completed when maiden heifer are turned out to grass for their second grazing. Knowing the number of days between turnout and breeding start date and the amount of weight heifers need to put on is critical to devise a management plan to ensure they achieve target weight.

New research
Currently, there is a new study being undertaken at Teagasc Moorepark which is examining the effect of the length of the milk feeding period (8-weeks or 12-weeks) and offering either a high or a low plane of nutrition in the post weaning period on weight gain, fertility and subsequent milk production. Preliminary results show that post-weaning nutrition is having a greater effect on weight gain than pre-weaning nutrition which indicates that if heifers are behind target at weaning offering a high plane of nutrition during the first (higher concentrate and grazing high quality grass to 4 – 4.5cm) and second (grazing high quality grass to 4 – 4.5cm) grazing seasons can ensure high growth rates and the attainment of target weight. However, the study needs to be completed and the effects on milk production investigated as previous international research indicates that milk feeding strategy may have a positive effect on milk production potential when heifers join the lactating herd.

Article by Emer Kennedy and Hazel Costigan of Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland

Today's farm magazine (July – August 2019). Rearing strategies for dairy heifers. Hazel Costigan. Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork

Alison Sinnott and Hazel Costigan.

Addressing the labour shortages associated with calf rearing

To maintain a sustainable future for our dairy farms, finding solutions to overcome the labour shortage associated with calf rearing is critical. We are carrying out research to evaluate how calf management practices can be advanced and streamlined in a way that improves labour using LEAN efficiency principals, without negatively affecting the calf.

The project began in spring 2019, with an initial investigation into the effect of automated calf feeding systems on calf health, welfare and labour. Further research will take place over the next four years to develop a comprehensive training programme and guide to rearing calves in an efficient and sustainable way.

Alison Sinnott

Rearing strategies for dairy heifers

Developing an optimum heifer-rearing strategy is becoming increasingly necessary; such a strategy must begin shortly after birth and continue until the heifer calves down.

In spring 2018, we began a three-year study at Teagasc Moorepark to investigate the effect of weaning age and post-weaning growth rate on growth performance, fertility parameters, age at first calving and first-lactation milk production of the maiden heifer.

Heifer calves were weaned at either eight or 12 weeks and subsequently offered either a high or low level of concentrates post-weaning. In the second year, grass was managed so that the heifers previously offered high and low levels of concentrates were grazed to 4.5 and 3.5 cm, respectively. To learn more visit us at Moorepark 2019.

Hazel Costigan

Becoming an employer of choice

As well as technical topics there will be a huge amount to learn about people management at Moorepark 19.

Work by Thomas Lawton, Suzanne Groome, Martina Gormley, Pat Clarke and Marion Beecher have shown that:

- **Good communication and training opportunities are the main characteristics employees seek from their employer**
- **77% of farmers surveyed do not issue payslips to employees**
- **Improvements required regarding fair treatment and respect of employees, including employers compliance with employment law**

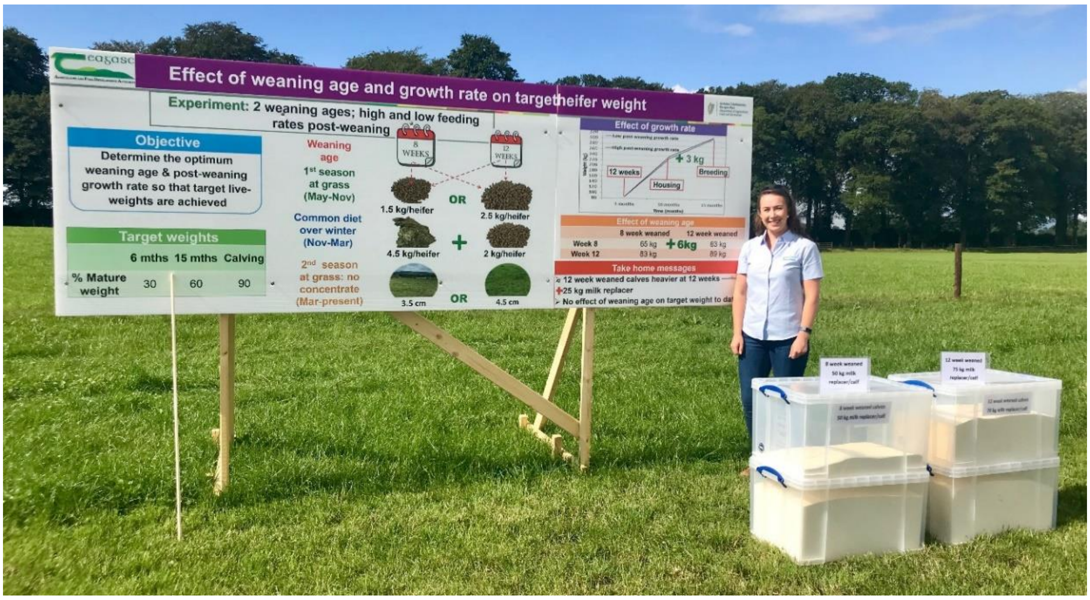
The Dairy Edge podcast (October 2019). Getting the heifer rearing process right. Emer Kennedy and Hazel Costigan. Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork

10.5 Open Days

AgriAware day 2018. Calf Rearing. Hazel Costigan. Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork.

AgriAware day 2019. Calf Rearing. Hazel Costigan. Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork.

Moorepark'19 *Irish dairying – growing sustainably*. Hazel Costigan. Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork.



Moorepark'21 *Irish dairying – delivering sustainability*. Hazel Costigan. Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork