Live weight and growth of dairy heifers are important for subsequent milk production and reproductive performance

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Rhiannon Clare Handcock

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Abstract

In the pasture-based farming systems that occur in New Zealand, dairy heifers tend to follow a seasonal pattern of growth in response to pasture quality and availability. The industry recommended liveweight-for-age targets for dairy heifers are 30% of mature liveweight (LWT) at 6 months of age, 60% at 15 months of age and 90% at first calving. Target growth rates are calculated by linear interpolation, thereby creating a mostly linear planned trajectory of growth from three to 22 months of age. The general aim of this thesis was to investigate the effects of LWT and growth on dairy heifer performance in the New Zealand pasture-based system.

In this thesis, LWT records from 189,936 spring-born dairy heifers were provided by Livestock Improvement Corporation to model growth curves from three to 22 months of age. Holstein-Friesian (F) heifers were heavier than Jersey (J) heifers from three to 22 months of age, and FxJ crossbred heifers were heavier than the mean of the purebreds due to positive heterosis effects. Additional data of calving dates and milk production records were provided by Livestock Improvement Corporation. Live weight between three and 21 months of age had significant impacts on milk production and reproductive performance. As LWT of heifers increased, milk production and probability of calving and calving early increased up to a maximum. Further increases in LWT past the maximum point did not result in increases in milk production, and for reproduction (stayability and calving rate) resulted in a decline in probability. For heifers that were below average in LWT, significant improvements to milk production and reproductive performance would be expected by increasing LWT. For example, the mean LWT of 15-month-old Holstein-Friesian-Jersey crossbred (FJ) heifers was 301.5 kg. These “average” heifers were estimated to produce 436 and 1,477 kg more energy-corrected milk (ECM) than “below average” 250 kg heifers in first-lactation and three-parity accumulated yields, respectively. Additionally, stayability to first, second and third calvings were superior for “average” heifers (93.6 vs 89.3% for first, 78.2 vs 70.6% for second and 64.7 vs 57.5% for third) and first calving 21-day calving rate (C21_2yo; 81.9 vs 78.0%) compared with “below average” heifers. For heifers that were above average in LWT, significant improvements to milk production would be expected by increasing LWT, however, at the heaviest LWTs a reduction in reproductive performance would be expected. For example, FJ heifers that were 375 kg at 15 months of age were estimated to produce 554 and 1,434 kg more ECM than “average” 300 kg heifers in first-lactation and three-parity accumulated yields, respectively. However, stayability and C21_2yo were similar for 375 kg (93.4%, 78.9%, 63.8% and 79.8% for stayability to first, second, third calving and C21_2yo, respectively) and 300 kg FJ heifers. Heifers that were at the heaviest LWTs, for example, 425 kg at 15 months of age were estimated to have the greatest ECM yields, but had a lower stayability and C21_2yo compared with "average" heifers (88.4%, 72.5%, 55.3% and 76.8% for stayability to first, second, third calving and C21_2yo, respectively). The greatest benefits to both reproduction and milk production would be expected by increasing LWT of the lightest heifers at each age studied.

In a prospective study, milk production did not differ between heifers that grew in a seasonal manner (slow then fast) compared with the target growth trajectory (linear) between six and 15 months of age. There was a difference in the age at which puberty was attained, such that heifers that grew to the target growth trajectory were younger at puberty compared with those grown in a seasonal manner, however, there was no difference between treatments in the date of first calving or first lactation milk production. These results indicate that there were limited disadvantages to growing heifers slower over their first winter, provided they caught up to target LWT by first mating.

Overall the results of this thesis indicate that having heifers heavier through the precalving rearing phase (three to 21 months of age) has the potential to improve reproductive success and milk production, with the greatest advantage seen by increasing LWT of the lightest heifers. This information can be used to develop guidelines which may improve productivity and survival of dairy cattle in New Zealand.

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List of Abbreviations

ADG	Average daily gain
AGR	Absolute growth rate
AI	Artificial insemination
AMR	Absolute maturing rate
BCS	Body Condition Score
BV	Breeding Value
BW	Breeding Worth
C21_2yo **C21_3yo** **C21_4yo**	Calving rate – proportion of heifers that calved within 21 days of PSC as a two-year-old (2yo), three-year-old (3yo) or four-year-old (4yo)
C2yo **C3yo** **C4yo**	First calving as a two-year-old (C2yo), second calving as a three-year-old (C3yo) or third calving as a four-year-old (C4yo)
CL	Corpus luteum
ECM	Energy-corrected milk
EV	Economic Value
F	Holstein-Friesian
FJ	Holstein-Friesian-Jersey crossbred
FX	Holstein-Friesian crossbred
J	Jersey
JX	Jersey crossbred
LWT	Live weight
MCP	Multiple-component pricing
mo	months
MS	Milksolids
MSTAY	Marginal stayability
pctLWT21	Proportion of 21-month LWT at 12 months of age
PPAI	Postpartum anoestrus interval
PSC	Planned start of calving
PSM	Planned start of mating
RC21_2yo	Re-calving rate – proportion of heifers that were reared that calved within 21 days of PSC
RC21_3yo **RC21_4yo**	Re-calving rate – proportion of heifers that calved the year prior (C2yo or C3yo) that calved within 21 days of PSC

RGR	Relative growth rate
RMR	Relative maturing rate
RPE	Relative prediction error
SR21	Submission rate (21 day)
STAY	Stayability

General Introduction

The New Zealand pasture-based dairy farming system requires matching the feed demand of the herd as closely as possible to the pasture growth rate throughout the year, therefore, it is important that replacement heifers attain puberty prior to their first mating period at 15 months of age in order to conceive within three weeks of the planned start of the mating (PSM). Following this, heifers are required to calve easily, produce above-average milk production and conceive within six weeks of PSM each year. Ultimately, the replacement heifers need to survive in the herd long enough to generate profit for the farmer/herd owner. Factors affecting any of these qualities will have an impact on farm profitability.

The industry recommended liveweight-for-age targets for dairy heifers are 30% of mature liveweight (LWT) at 6 months of age, 60% of mature LWT at 15 months of age and 90% of mature LWT at first calving (Burke et al. 2007). These target LWTs were suggested by Troccon (1993) based on the effects of winter feeding on the performance of French Friesian heifers born in autumn. A New Zealand study on Friesian and Jersey heifers designed to quantify the benefits from better-reared heifers concluded that the targets provided by Troccon (1993) "appeared sound in a New Zealand system" (Penno 1997). These targets have been further broken down to 20% at three, 40% at nine, 50% at 12, 73% at 18 and 86% at 21 months of age (DairyNZ 2018h). Target growth rates are calculated by linear interpolation between the target LWTs, thereby creating a mostly linear planned trajectory of growth from three to 22 months of age. Due to the seasonal variations in pasture quality and quantity that occurs in the New Zealand pasture-based farming system (Litherland et al. 2002), dairy heifer LWT and growth pattern exhibit marked fluctuations from birth until first calving (Handcock et al. 2016; McNaughton & Lopdell 2012), and so do not follow the linear trajectory that the targets dictate. Furthermore, mature LWT of young heifers is only known once the heifers reach maturity. The current recommended method to estimate mature LWT is to add 500 kg to the average LWT breeding value (BV) of a line of heifers and to use this value to calculate target LWTs. Therefore, under- or overprediction of mature LWT would result in heifers being under- or overgrown in relation to their target LWT.

The Holstein-Friesian Jersey crossbreed is the dominant breed category in New Zealand (47.8%), followed by Holstein-Friesian (33.4%), Jersey (9.0%) and "Other" breeds (9.7%; Ayrshire, Milking Shorthorn, Guernsey, Brown Swiss and remaining crossbreeds) (Livestock Improvement Corporation & DairyNZ 2018). The majority of studies on reproductive performance and milk production as related to LWT or growth are completed on heifers of Holstein or Holstein-Friesian breed makeup (Archbold et al. 2012; Davis Rincker et al. 2011; Dobos et al. 2001; Ducker et al. 1982; Lammers et al. 1999; Raeth-Knight et al. 2009; Van Eetvelde et al. 2017), with limited studies including Jersey and/or crossbreeds (Macdonald et al. 2005; McNaughton & Lopdell 2013; van der Waaij et al. 1997; Vargas et al. 1998). Due to the large proportion of crossbred animals in the New Zealand herd, it is important to determine whether the effects of LWT or growth on milk production differ among breeds. The general aim of this thesis was to investigate the effects of LWT and growth on dairy heifer performance in the New Zealand pasture-based system.

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

- To model growth curves of New Zealand dairy heifers of F, J and FxJ crossbreed makeup to estimate their LWT and growth from three to 22 months of age.
- To use the estimated LWTs from three to 21 months of age to understand the relationships between precalving LWTs and milk production and precalving LWTs and reproduction and survival in New Zealand dairy heifers.
- To retrospectively and prospectively explore the relationships between growth pattern during rearing and subsequent milk production and reproductive performance.

The outcome of this research will allow for further development of dairy heifer target LWT and growth trajectories to maximise reproductive performance and milk production. It will provide a foundation for future research in critical periods of heifer development and in economics of heifer rearing. Furthermore, it has the potential to be used by farmers and graziers to influence future productivity of dairy heifers through management of their LWT during rearing.

Chapter 1 Review of Literature

1.1 New Zealand's Dairy Industry

The New Zealand dairy production system is based on converting pasture into milk by grazing dairy cattle (Holmes et al. 2007c). The system is seasonal and is designed to match the feed demand of the herd as close as possible to the pasture growth rate throughout the year. This can be achieved by using an appropriate stocking rate (cows per hectare) that will dictate the overall feed demand per hectare, and by calving and drying-off the herd at appropriate times (Spaans et al. 2018). The system is illustrated diagrammatically in Figure 1.1 below.

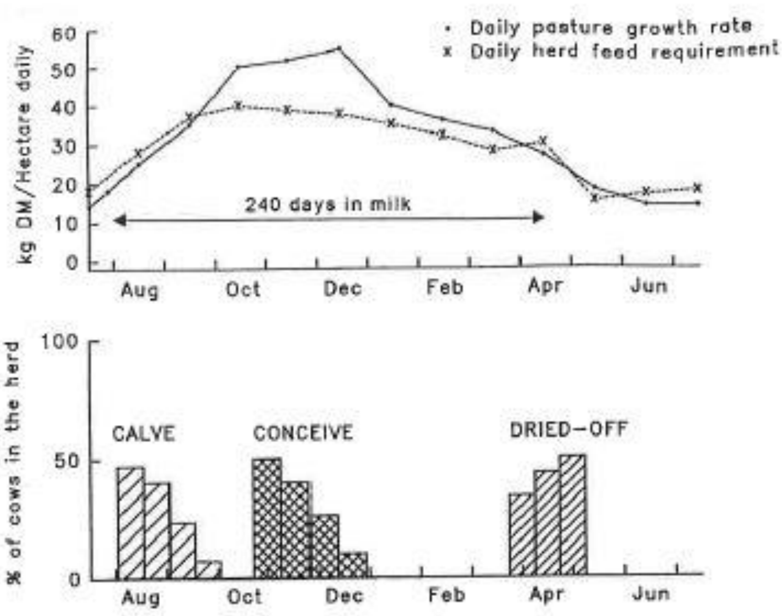

Figure 1.1 Example of the seasonal pattern of calving, mating and drying-off to synchronise daily pasture growth rate and daily herd feed requirements (Holmes et al. 2007c).

Calving and drying-off dates are important feed management decisions that will affect the pattern of feed demand and ensure it is matched to the pattern of feed supply (Holmes et al. 2007b). The calving date is determined by the previous year's mating, the drying-off date is a decision made in the current season based on pasture covers, cow condition and the weather (Holmes et al. 2007b).

The predominant pasture used in New Zealand farming systems is a ryegrass and white clover pasture (Holmes et al. 2007c; Litherland et al. 2002; Waghorn & Clark 2004). The growth of this pasture is seasonal, with faster growth occurring over spring and slower growth during winter (Holmes et al. 2007c). It is often green, leafy and of high quality in the spring (Litherland et al. 2002; Waghorn & Clark 2004), with stem and seed-head formation occurring in late spring and early summer (Waghorn & Clark 2004). The growth and quality of the sward improves in autumn, but growth rate decreases in winter, thereby limiting feed availability (Holmes et al. 2007c; Waghorn & Clark 2004). The seasonal trends are similar in dairy and sheep and beef farms, but dairy farms generally have greater pasture quality (Table 1.1 and Table 1.2).

Table 1.1 Average herbage quality of New Zealand Sheep and Beef farms in summer, spring, autumn and winter.

Season and Location	ME (MJME/ kgDM)	CP (%)	ME:CP	NDF	Source
Summer					
Waikato	8.5	17.7	0.48	55	Litherland et al. (2002)
Tararua	10	18.1	0.55	47	Litherland et al. (2002)
Canterbury	9	20.2	0.45	51	Litherland et al. (2002)
Southland	10	19.7	0.51	51	Litherland et al. (2002)
Manawatu	10.9	23.1	0.47	39.8	Machado et al. (2005)
Average summer	**9.7**	**19.8**	**0.49**	**48.8**	
Autumn					
Waikato	8.1	18.8	0.43	57	Litherland et al. (2002)
Tararua	9.2	21.9	0.42	50	Litherland et al. (2002)
Canterbury	7.6	13.9	0.55	57	Litherland et al. (2002)
Southland	10	20.3	0.49	52	Litherland et al. (2002)
Manawatu	10.9	26.4	0.41	40.4	Machado et al. (2005)
Average autumn	**9.2**	**20.3**	**0.46**	**51.3**	
Winter					
Waikato	9.8	24.2	0.40	49	Litherland et al. (2002)
Tararua	10.6	23.3	0.45	48	Litherland et al. (2002)
Canterbury	9.5	19.9	0.48	49	Litherland et al. (2002)
Southland	11.3	27.4	0.41	46	Litherland et al. (2002)
Manawatu	11.6	26.7	0.43	40.8	Machado et al. (2005)
Average winter	**10.6**	**24.3**	**0.43**	**46.6**	
Spring					
Waikato	10.3	22.6	0.46	50	Litherland et al. (2002)
Tararua	11.6	24.4	0.48	42	Litherland et al. (2002)
Canterbury	10.8	21.5	0.50	43	Litherland et al. (2002)
Southland	11.4	24.4	0.47	48	Litherland et al. (2002)
Manawatu	11.8	26.9	0.44	38.8	Machado et al. (2005)
Average spring	**11.2**	**24.0**	**0.47**	**44.4**	

Table 1.2 Average herbage quality of New Zealand Dairy farms in summer, spring, autumn and winter.

Season and Location	ME (MJME/kgDM)	CP (%)	ME:CP	NDF	Source
Summer					
Canterbury	11.7	20.7	0.57	39.1	1
Waikato and Manawatu	11.2	21.4	0.52	43.3	2
North-North Island	11.7	21	0.56	-	3
South-North Island	10.7	20.5	0.52	-	3
South Island	10.8	21.5	0.50	-	3
Average	**11.2**	**21.0**	**0.53**	**41.2**	
Autumn					
Canterbury	12.0	20.9	0.57	37.3	1
Waikato and Manawatu	12.5	25.8	0.48	38.5	2
North-North Island	10.7	21	0.51	-	3
South-North Island	10.8	23	0.47	-	3
South Island	11	23.5	0.47	-	3
Average	**11.4**	**22.8**	**0.50**	**37.9**	
Winter					
Canterbury	12.6	18.2	0.69	36.6	1
Waikato and Manawatu	12.0	22.9	0.52	36.1	2
North-North Island	11	22	0.50	-	3
South-North Island	11.3	24	0.47	-	3
South Island	10.8	24	0.45	-	3
Average	**11.5**	**22.2**	**0.53**	**36.4**	
Spring					
Canterbury	12.3	19.5	0.63	37.1	1
Waikato and Manawatu	12.1	23.6	0.51	36.2	2
North-North Island	11.5	22	0.52	-	3
South-North Island	11.4	22	0.52	-	3
South Island	10.9	21.3	0.51	-	3
Average	**11.6**	**21.7**	**0.54**	**36.7**	

1 South Island Dairying Development Centre (2015), 2 Moller (1997), 3 Litherland and Lambert (2007).

There is often a reduction in pasture quality during summer as pasture growth rate is restricted by the limited soil moisture availability (Waghorn & Clark 2004). The decline in pasture quality in summer is also due to a high proportion of dead matter and reproductive stem that contain large amounts of fibre (Litherland et al. 2002). Pastures with a high fibre content are digested slowly because they must be chewed sufficiently to break down cell walls and enable rumen microbes to digest cell components (Waghorn et al. 2007). The high fibre content and slow digestion of mature pasture can limit animal intakes of energy and protein, consequently limiting animal performance (Burke et al. 2002; Litherland et al. 2002).

During summer, providing an adequate pasture allowance may be insufficient to support high animal performance because the low pasture quality limits the ability to consume enough nutrients (Litherland et al. 2002). During winter, low soil temperatures limit pasture growth rates and therefore, low quantities of pasture available may restrict animal performance (Burke et al. 2002). During these periods of low pasture quality or availability, higher quality feeds should be considered as a supplement to sustain animal performance (Burke et al. 2002).

In order to maintain the close relationship between pasture supply and demand, cows must calve at the same time each year; so a calving interval of 365 days is important in the New Zealand system (Holmes et al. 2007b). The planned start of mating (PSM) date determines the planned start of calving (PSC) date, as the gestation length of cows is approximately 282 days (Donkersloot 2014; Haile-Mariam & Pryce 2019).

The mammary gland must have a period of not lactating (dry period) in order to recover and regenerate before the commencement of the next lactation (Capuco et al. 1997; Holmes et al. 2007b). The traditional, Northern Hemisphere recommended dry period length was 60 days (Capuco et al. 1997; Swanson 1965), which leaves a 305-day lactation to maintain a 365-day calving interval in a seasonal system. Recent studies advocate a shorter (30 – 40 day) dry period to improve the negative energy balance in early lactation in Northern Hemisphere systems (Khazanehei et al. 2015; van Knegsel et al. 2014).

The average lactation length in New Zealand is generally less than the lactation length that occurs in Northern Hemisphere systems; due to feed availability and the spread of calving. For example, the herd in Figure 1.1 commences calving on the 1st August and ends on the 30th September. In order to lactate for 305 days, the first cow to calve would be dried off on the 2nd June and the last cow to calve would be dried off on the 31st July. For a New Zealand seasonal pasture-based farmer this system would be impractical, it makes more sense to dry-off the majority of the herd at one time rather than staggering it over a prolonged period. The main goals of the seasonal pasture-based dairy farmer pre-calving are to have sufficient pasture covers to feed the lactating cows until the spring flush of growth arrives, and to have all cows calving at a reasonable body condition score; between 5.0 and 5.5 (Burke et al. 2007). As described previously the pasture growth slows as winter approaches, in order to have enough pasture on the dairy platform when calving commences the herd feed demand needs to be low pre-calving, which can be achieved by ending lactation. For the 2017/18 season the average lactation length was 274 days (91 day dry period) based on milk tanker pick up information (Livestock Improvement Corporation & DairyNZ 2018).

The New Zealand dairy industry consists of 4,992,914 cows spread among 11,590 herds (Livestock Improvement Corporation & DairyNZ 2018). The majority of these herds are in the North Island (72%), including 28.7% in the Waikato region. The South Island has larger herds (635 cows) than the North Island (352 cows) and has greater per cow (397 vs 349 kg) and per hectare (1,176 vs 966 kg) milk solids production (Livestock Improvement Corporation & DairyNZ 2018). The Holstein-Friesian Jersey crossbreed (FxJ) is the dominant breed category in New Zealand (47.8%), followed by Holstein-Friesian (F; 33.4%), Jersey (J; 9.0%) and “Other” breeds (O; 9.7%; Ayrshire, Milking Shorthorn, Guernsey, Brown Swiss and remaining crossbreeds) (Livestock Improvement Corporation & DairyNZ 2018). In 2005, these percentages were 28%, 48%, 15% and 8% for FxJ, F, J and O, respectively (Livestock Improvement Corporation 2005); which shows an increase in crossbreeding of F and J cattle and an increased availability of crossbred bulls. Unsurprisingly, as Xu and Burton (2003) reported that crossbred cows had approximately 2% greater six-week in-calf rate compared with F and J cows and Lembeye et al. (2016) reported that there were positive heterosis effects on milk production in the first five lactations. Within the FxJ breed category there is a large range of Holstein-Friesian and Jersey breed proportions.

Phenotypically, J cattle are lighter and earlier maturing than F and FxJ (Burke et al. 1998; Leche 1971). In addition, there is considerable variation in LWT breeding values (which are estimates of mature LWT) within Friesian (-33.3 – 104.7 kg), Jersey (-85.5 – -6 kg) and Friesian-Jersey crossbred bulls (-51.3 – 51.9 kg) (DairyNZ 2018f).

Further breed differences include that 15-month-old F heifers had higher conception rates and pregnancy rates (Xu & Burton 1999) and lower nonpregnancy rates (MacMillan 1994; Xu & Burton 1999) compared with J heifers. In addition, Xu and Burton (1999) and Grosshans et al. (1997) reported that 15-month F heifers had superior reproductive performance to J heifers, whereas the performance of J cows exceeded that of F cows during first and second lactations. In contrast, Spaans et al. (2018) reported that although J cows had shorter days to first oestrus and a lower proportion not detected in oestrus at the start of mating compared with F cows, the final conception rates and pregnancy rates of F and J cows were not different. In terms of milk production, it is well reported that J cows produced lower milk volume than F cows (Lembeye et al. 2016; Sneddon et al. 2016a).

1.1.2 Measures of milk production

All New Zealand milk payment systems are based on a multiple-component pricing system (MCP) (Sneddon et al. 2013). An MCP is the pricing of milk on the basis of more than one component, each rewarded differently (Emmons et al. 1990). The prominent dairy processor in New Zealand is Fonterra Co-operative Group. The payment system used by Fonterra is the 'A + B - C' formula, where 'A' and 'B' are the values per kg of fat and protein and 'C' represents the processing cost per litre of milk volume (Sneddon et al. 2013). Due to this pricing system, studies of New Zealand cattle generally express milk production as kg of milksolids, which is the sum of fat and protein production.

Internationally, milk payment systems differ to those in New Zealand and include payment per litre of milk (e.g. Australia), per kg of milk (e.g. Netherlands and Denmark), or in the USA a complicated class system roughly based on a per hundred weight (100 pounds) of milk (Sneddon et al. 2013). Due to the different payment systems throughout the world, cows have been selected to produce milk with differing fat and protein concentrations. For example, in New Zealand cows have been selected for high fat and protein concentrations, whereas, in the USA cows have been selected for high milk volumes and hence lower concentrations of fat and protein. This makes comparison of studies on milk production difficult as one litre of milk from a New Zealand cow differs to one litre of milk from a USA cow. Therefore, standardising milk to a set composition of fat and protein allows for comparisons among studies. One method is to calculate energy-corrected milk (ECM) as used by Beever and Doyle (2007), and derived from Tyrell and Reid (1965) as:

ECM = milk yield × (383 × fat percentage + 242 × protein percentage + 783.2)/3,140

As well as allowing for comparisons between international studies, calculating ECM yields allows for comparisons among different breeds (and crossbreeds) of dairy cattle, as fat and protein concentrations can differ among breeds (Oldenbroek 1988; Sneddon et al. 2016b). For example, fat and protein concentrations are greater for New Zealand Jersey cattle (5.3% and 3.9%, respectively) compared with Holstein-Friesian cattle (4.6% and 3.7%, respectively) (Sneddon et al. 2016b).

1.1.3 Measures of reproductive performance

In order to maintain the close relationship between pasture supply and animal feed demand in a seasonal pasture-based system, cows must calve at the same time each year. Additionally, the majority of the cows in the herd are dried off around the same time, therefore, cows that calved earlier in the calving period will have had a longer lactation compared with cows that calved later, enabling more productive days and hence greater milk yields (Macdonald et al. 2008). As mentioned previously, the PSM date determines the PSC date; after PSM date, every cow detected in oestrus will be bred regardless of how long ago she calved. The main goal is to get as many cows pregnant as quickly as possible in order to achieve a compact calving pattern the next year. Therefore, minimising the time between calving and first oestrus (postpartum anoestrus interval; PPAI) is important. The average length of the mating period was 76 days (10-11 weeks) for herds milked twice-a-day in New Zealand (Hemming et al. 2018), after which cows that are detected in oestrus will no longer be mated.

Interval traits such as interval from calving to first service and interval from calving to conception (days open) that are often used in non-seasonal systems, are generally not suitable reproductive measures in a seasonal system where cows that calve early are withheld from being submitted for mating (even if they are in oestrus) until PSM (Bowley et al. 2015; McNaughton et al. 2007). Therefore, the interval from calving to first service or conception is long for early calving cows, as well as cows with poor fertility (McNaughton et al. 2007). Using intervals from PSM or PSC are therefore advised in seasonal systems.

A measure of reproductive performance in seasonal-calving herds is the six-week in-calf rate; the percentage of the herd that became pregnant within six weeks of PSM (Bowley et al. 2015). The six-week in-calf rate is driven by the 21-day submission rate (SR21; proportion of the herd submitted for mating in the first 21 days from PSM) and the probability of pregnancy at each insemination (Brownlie et al. 2014). The six-week in-calf rate can only be determined reliably when early aged-pregnancy diagnosis is performed (Hemming et al. 2018). In large-scale analyses where early aged pregnancy diagnosis is not performed (or recorded) for all animals, the percentage of cows calving within 21 or 42 days of PSC can be estimated and used to compare reproductive performance (Brownlie 2012).

Calving rates can be calculated based on animals that calved that year (calved within 21 days in year 'n' provided they calved in year 'n'; calving rate, C21) or based on animals that calved the year prior (calved within 21 days in year 'n' provided they calved in year 'n-1'; re-calving rate, RC21). Industry targets for calving rates are 75% of first calvers calved within 21 days of PSC and 60% of the whole herd calved within 21 days of PSC (DairyNZ 2018c). Re-calving rates can be used as a proxy measure for in-calf rates when no pregnancy diagnosis information is available (Brownlie 2012; DairyNZ 2018e). Re-calving rates should be interpreted as only estimates for in-calf rates (DairyNZ 2018e), due to the variable proportion of animals that do not calve for reasons other than failure to conceive and maintain a pregnancy. However, treating females that did not calve as missing (i.e. C21) does not account for an important source of variation in fertility (Donoghue et al. 2004), as females that failed to calve also failed to calve within 21 days. In the model for genetic evaluation of dairy cow fertility in New Zealand, the key fertility traits included are 42-day calving rate (in second, third and fourth calvings), SR21 (in first, second and third lactations) and calving interval (first to second calving) (NZAEL 2016).

Each year a proportion of the milking herd are removed/culled for various reasons including reproductive status (35%), health issues (17%), age (4%) and milk production (8.6%) (Kerslake et al. 2018). Therefore, there need to be new cows entering the herd to replace the cull cows, these are called replacements. Generally, replacements are generated from the calves born each year but can also be purchased from outside of the herd (Holmes et al. 2007a). Based on the 2017/18 seasons, 18-24% of herd-tested cows were two years of age (Livestock Improvement Corporation & DairyNZ 2018). Indicating that approximately 21% of the herd is replaced each year with two-year-old heifers. This equates to approximately one million dairy heifers reared per year in New Zealand.

1.1.4 Replacement dairy heifers

The system chosen to rear replacement heifers from birth to first-calving may differ depending on the farm system. These include rearing the heifers from birth to calving on the dairy platform, sending them to a calf rearer until weaning, and grazing off-farm until a few months prior to calving, or a combination of both (Bryant & McRobbie 1991; Holmes et al. 2007a; Moran 1996). The ability to rear heifers off the dairy platform enables more of the feed grown to be allocated for milk production rather than for heifer growth (Bryant & McRobbie 1991; Holmes et al. 2007a). It is assumed that the majority of heifers are grazed off the dairy platform, but the exact proportions are unknown.

As mentioned previously, the predominant forage used in New Zealand farming systems is a ryegrass and white clover pasture (Holmes et al. 2007c; Litherland et al. 2002; Waghorn & Clark 2004). The quantity and quality of pasture varies over the year and the live weights (LWT) of dairy heifers tends to follow a similar pattern (Back et al. 2017; Handcock et al. 2016; McNaughton & Lopdell 2012). In addition, there were differences among breed groups for growth rate from birth to 21 months of age (Back et al. 2017).

1.2 Live weight and Growth

Live weight at any time point can be partitioned into the mature LWT eventually attained and the percentage of mature LWT at the time point in question (Fitzhugh & Taylor 1971). For example, the LWT of a heifer at 12 months of age (250 kg) is made up of her mature LWT (500 kg) and the percentage of maturity she was at 12 months of age (50% x 500 kg = 250 kg). In retrospective studies, where mature LWT is well recorded, the percentage of maturity can be accurately estimated at any given time point. In prospective studies, where animals are yet to attain maturity, the percentage of maturity is difficult to estimate as actual mature LWT is unknown due to the absence of mature LWT records.

A definition of mature size is “the final size eventually reached” (Fitzhugh & Taylor 1971) or the asymptote of a fitted growth curve (Coop 1973; Fitzhugh & Taylor 1971;

Garcia-Muniz et al. 1998; von Bertalanffy 1957). These definitions are well suited to traits such as height and length, which do not show negative growth but may be inadequate for measures such as LWT, where variation due to the environment can positively or negatively influence it (Bakker & Koops 1977; Fitzhugh & Taylor 1971). Accurate estimates of mature LWT can be obtained when animals are fed to ad libitum or to their genetic potential (Coop 1973; Fitzhugh & Taylor 1971). The majority of high country breeding ewes in a New Zealand study, never reached their potential size due to a restricted nutritional environment and the annual burden of producing and suckling a lamb (Coop 1973). No similar study has been completed on dairy cattle in New Zealand, but due to the pasture-based system, it is unlikely that they will have sufficient nutrient intakes to reach their genetic potential for LWT (Kolver & Muller 1998). For example, New Zealand Holstein-Friesians that were fed a total mixed ration (TMR) during lactation were on average 61 kg heavier (556 vs 495 kg) than those fed a pasture-based diet (Kolver et al. 2002). However, at the end of lactation the mean body condition score (BCS) was 7.6 for TMR-fed cows compared with 5.0 for pasture-fed cows (Kolver et al. 2002). In the study by Kolver et al. (2002), measures of stature were not reported, therefore, New Zealand cows that were fed TMR were heavier and fatter, but it was not known whether they were closer to maturity than those fed pasture.

A method to measure mature LWT is to take the average over multiple years, after the growth of skeletal and muscle tissue has ceased (Fitzhugh & Taylor 1971). This method reduced the variation in LWT caused by the environment, such as lactation and gestation (Brinks et al. 1962; Fitzhugh & Taylor 1971). Currently for the purposes of LWT targets for dairy heifers (which will be discussed in Section 1.2.3), and genetic evaluation of LWT, mature LWT is considered to occur between six to eight years of age (DairyNZ 2015a, b). For the purpose of Animal Evaluation production traits (milk, fat and protein yields), five to seven years of age is used as maturity (DairyNZ 2016a).

Differences between animals that are the same age and from the same herd tend to reflect differences in mature LWT (Fitzhugh & Taylor 1971). Archbold et al. (2012) reported that Holstein-Friesian heifers (from 48 farms) that were lighter at mating start date (approximately 15 months of age) were also lighter during first, second and third lactations than heifers that were heavier at mating start date. Further providing evidence that differences at younger ages were reflective of mature LWT, either due to genetics or due to early-in-life growth restricting mature LWT. In addition, animals that have heavy mature LWT are generally later maturing compared with animals that have lighter mature LWT (Taylor 1965). Similarly, animals that were heavier at maturity tended to be a lesser percentage of mature LWT at the same age compared with animals that were lighter at maturity (Fitzhugh & Taylor 1971).

A key factor that influences mature LWT, LWT at a given age and growth is breed. Jerseys and their crosses are lighter than Holstein-Friesians and their crosses from birth to maturity in both pasture-based and confinement systems (Burke et al. 1998; Butler-Hogg & Wood 1982; Leche 1971; Spaans et al. 2018). In addition, Jersey cattle are considered to be early-maturing compared with Holstein-Friesian cattle (Hickson et al. 2011; Leche 1971). Because of this, breed and LWT are considered to be confounded; for example, heavier heifers are more likely to have more Holstein-Friesian breed proportions than lighter heifers. Therefore, in multi-breed models of LWT for age, breed and LWT cannot be included as fixed effects in the same model, as the two are confounded. A method to control for confounding in statistical analysis is through stratification of the confounding variable (Pourhoseingholi et al. 2012). For example, a model to estimate the effect of LWT on milk production with multiple breeds could control for confounding of LWT and breed by stratifying breed from more to less Holstein-Friesian and nesting LWT within the stratified breed categories.

Comparisons between breeds (or animals) in the rate of maturing can be estimated using the absolute maturing rate (AMR) or the relative maturing rate (RMR). Which can be calculated using the following formulae:

$$AMR = \left(\frac{\mathrm{LWT}_2}{Mature} - \frac{\mathrm{LWT}_1}{Mature}\right) \Big/ (t_2 - t_1)$$

$$RMR = \left(\ln\left(\frac{\mathrm{LWT}_2}{Mature}\right) - \ln\left(\frac{\mathrm{LWT}_1}{Mature}\right)\right) \Big/ (t_2 - t_1)$$

where t_1 is the initial age, t_2 is the final age, and LWT_1 and LWT_2 are the corresponding LWTs at these ages and mature is the mature LWT (Fitzhugh & Taylor 1971).

A second major factor influencing LWT and growth is feed quality and availability. As mentioned earlier (Section 1.1.4), the growth of New Zealand dairy heifers tends to follow the seasonal variation in quantity and quality of pasture (Handcock et al. 2016; McNaughton & Lopdell 2012). In the analysis by McNaughton and Lopdell (2012), heifers during their first autumn/winter (nine - 12 months of age) had very low growth rates (0.32 kg/d), however, over the following spring period (12 – 15 months of age) heifers grew faster (0.65 kg/d). A subsequent study indicated that heifer growth had improved from 2010 to 2015, however, heifers were still growing in a seasonal pattern of slow over winter and fast over spring (Handcock et al. 2016).

Barash et al. (1994) reported that heifers fed in a "stair-step" regimen of a restricted followed by a compensatory diet were similar in LWT but shorter in hip height compared with heifers fed to attain a constant 0.65 kg/d of LWT gain at the completion of the compensatory period. It was concluded that the "stair-step" fed heifers were using energy for fat gain rather than lean-tissue gain (Barash et al. 1994), and hence were "shorter and fatter" than their constant growth rate contemporaries at similar LWT.

Over the summer period, when ryegrass-white clover pasture growth rate is restricted and pasture quality declines (Section 1.1), the growth of heifers can be modified by feeding alternative forages. Heifers fed forages made up of lucerne, or chicory, plantain, and clover had greater growth rates compared with heifers fed a traditional pasture diet only (Handcock et al. 2015). Differences were attributed to the greater energy, protein and digestibility of the alternative forages compared with pasture (Handcock et al. 2015). Likewise, Friesian bull calves fed a "herb sward" of chicory, plantain and clover had superior LWT gains compared with bulls fed a traditional pasture diet (Pettigrew et al. 2016). In addition, bulls that grazed a traditional pasture diet and supplemented with concentrates had superior LWT gains to those grazed a traditional pasture diet only (Pettigrew et al. 2016). These studies demonstrate that heifer growth can be improved by offering alternative, higher quality feed during periods of low pasture availability.

1.2.1 Ways to model LWT and growth

The simplest model to describe the relationship between size and age is average daily gain (or absolute growth rate; AGR) between two points as ($LWT_2 - LWT_1$) / ($t_2 - t_1$). In addition, the relative growth rate (RGR) can be calculated to provide an estimate of the AGR, relative to the initial LWT as (ln (LWT_2) – ln (LWT_1)) / ($t_2 - t_1$). However, the use of AGR or RGR is only useful for short periods of growth and does not provide much insight into the pattern of growth over time (Fitzhugh 1976). Despite this, the RGR is equivalent to the RMR, as demonstrated by Fitzhugh and Taylor (1971), and can be used as an estimation of maturing rate in the absence of mature LWT data.

As can be determined by the equation, AGR over a set period is related to LWT and growth rate prior to and after the growth period studied. For example, an animal that had a small initial LWT but had a fast AGR would end up with a lighter final LWT compared with an animal that had a heavier initial LWT but grew at the same AGR. Therefore, it is important when analysing the effects of growth or AGR on a particular variable to disentangle whether it is the initial LWT, final LWT or AGR that is having the greatest effect.

Common growth models for lifetime LWT-age relationships of animals are nonlinear models, such as the logistic, Gompertz, Brody, von Bertalanffy and Richards functions (Fitzhugh 1976). Parameters within these nonlinear models generally have a biological interpretation. For example; the parameter "A" is the asymptote of the curve which represents mature LWT of the animal, and "k" is the maturing index which is a measure of growth rate and the rate of change of growth rate (Fitzhugh 1976). The equations for some of the more common nonlinear growth models are displayed in Table 1.3 below.

Table 1.3 Equations of common growth models for animals.

	Equation for LWT =
Logistic	$A(1+\ be^{-kt})^{-1}$
Gompertz	$Ae^{(-be^{-kt})}$
Brody	$A(1-\ be^{-kt})$
Von Bertalanffy	$A(1-\ be^{-kt})^3$
Richards	$A(1\pm\ be^{-kt})^M$

Where A is asymptote for mature LWT, b is scaling parameter (constant of integration), e is exponential, k is function of the ratio of maximum growth rate to mature LWT (maturing index), t is time (generally age, in days) and M is the inflection parameter which establishes percentage of maturity at the point of inflection.

If LWT records are only available during the ascending phase of growth; i.e. before maturity, nonlinear models as described in Table 1.3 are not appropriate due to there being no estimate of "A"; mature LWT. Additionally, large fluctuations in LWT-age relationships are common, for example; feed shortages, feed surpluses and gestation. The models listed above smooth the fluctuations observed in the actual data, as they assume a monotonic increase in LWT from origin to asymptote (Fitzhugh 1976).

Random regression models have been used to model the changes in growth over time in beef cattle (Iwaisaki et al. 2005). In particular, Legendre polynomials of age have been used for genetic analyses of LWTs for beef cattle (Meyer 1999; Nobre et al. 2003) and for phenotypic LWT changes during lactation of dairy cattle (Sneddon et al. 2017). Modelling growth using Legendre polynomials provides advantages over nonlinear models, as records on mature LWT are not required for accurate estimation of LWT. In addition, random regression of polynomial models allows for seasonal fluctuations in LWT-age relationships that nonlinear models do not. In cases where the seasonal variations of LWT are of interest, random regression of Legendre polynomials are more suited than nonlinear models. However, the estimation of LWT at the extremes of the trajectory, or where the data is sparse can be poor when modelled with Legendre polynomials (Meyer 1999).

Another common method to measure/estimate LWT is to use correlated measures such as heart girth circumference (Pietersma et al. 2006), height, angularity, and/or BCS (Haile-Mariam et al. 2014) and to calibrate these measures to actual LWT records. In the study by Haile-Mariam et al. (2014), the visual assessment of LWT was the closest at predicting actual LWT (r^2=0.61) followed by the combination of stature, chest width, bone quality, udder depth, central ligament, muzzle width and BCS (r^2=0.47). This study indicates that although other measures can be used to predict LWT, the physical weighing of cattle is a superior method.

1.2.2 Genetic evaluation of live weight

The New Zealand National Breeding Objective for dairy cattle is to breed "animals whose progeny will be the most efficient converters of feed into farmer profit" (DairyNZ 2018a). The index used to rank cattle on the objective is Breeding Worth (BW), which measures the expected ability of cattle to breed replacements to meet the objective compared with the "genetic base cow" in dollars per 5.0 t DM eaten (DairyNZ 2016b, 2018a). From June 2016 the genetic base cow was the average of 21,585 cows born in 2005 (DairyNZ 2016b).

From February 2018, there were eight traits included in BW; milkfat, protein, milk volume, LWT, fertility, somatic cell score, residual survival and BCS (DairyNZ 2018a). Economic values (EVs) are estimates of the dollar value that a particular trait has to a farmer, and are routinely updated in February each year (DairyNZ 2018d). The EVs used for the 2018 season are in Table 1.4 below.

Table 1.4 The effective emphasis and economic values of the traits that make up Breeding Worth in 2018. Source DairyNZ (2018d).

Trait	Emphasis (%)	Economic Value ($/unit)
Milkfat (kg)	16	2.85
Protein (kg)	23	6.06
Milk Volume (litre)	12	-0.088
Liveweight (kg)	10	-1.30
Fertility (%)	14	6.55
Somatic Cell Score (unit)	7	-38.33
Residual Survival (day)	11	0.124
Body Condition Score (unit)	7	100.6

Economic values are combined with estimated breeding values (BVs) to make up an animal's BW as in the equation below (DairyNZ 2018a).

$$\begin{aligned} BW \ &= BV_{FAT} \times EV_{FAT} \\ &+ BV_{PROTEIN} \times EV_{PROTEIN} \\ &+ BV_{MILK\ VOLUME} \times EV_{MILK\ VOLUME} \\ &+ BV_{LIVEWEIGHT} \times EV_{LIVEWEIGHT} \\ &+ BV_{FERTILITY} \times EV_{FERTILITY} \\ &+ BV_{SOMATIC\ CELL\ SCORE} \times EV_{SOMATIC\ CELL\ SCORE} \\ &+ BV_{RESIDUAL\ SURVIVAL} \times EV_{RESIDUAL\ SURVIVAL} \\ &+ BV_{BODY\ CONDITION\ SCORE} \times EV_{BODY\ CONDITION\ SCORE} \end{aligned}$$

Breeding values are estimates of the animal's genetic merit for the trait concerned, calculated using data collected from individuals, ancestral and progeny records (DairyNZ 2018a). Each of the BVs for the animals are reported relative to the genetic base cow that has BVs set to zero (DairyNZ 2016b). Although not included in BW there are other traits that have BVs estimated including: lactation persistency, gestation length and calving difficulty (DairyNZ 2018b).

The genetic evaluation of LWT for the New Zealand dairy industry is of mature LWT and is included in BW to select cows that produce more milksolids per kg of LWT (DairyNZ 2018a). Liveweight is recognised as an important economic trait in dairy cattle that has been included in BW since its introduction in 1996 (DairyNZ 2015b, 2018a). This is due to the positive correlation between milk production and LWT (Table 1.5); as increased milk production is selected for, LWT will also increase. With increasing LWT there is increasing maintenance feed requirements, and therefore costs. As the objective is to breed efficient cows, by including LWT in BW and having a negative economic value attached to it (Table 1.4), cows will be selected to produce more milksolids per kg of LWT. The LWT of dairy cattle is a moderately heritable trait (Table 1.6).

Table 1.5 Genetic and phenotypic correlations between live weight (LWT) and milk production traits.

Source	Breed, Age and Country	Milk fat (kg)	Milk protein (kg)	Milk (kg)	Milk fat (%)	Milk protein (%)
Live weight- genetic						
1	HF 2yo, NZ	0.34	0.37	0.39	-0.09	-0.10
1	J 2yo, NZ	0.34	0.39	0.29	0.08	0.16
2	Mixed 2yo, NZ	0.33	0.36	0.28	-	-
3	Mixed 9mo, NZ	0.14	0.35	0.31		
3	Mixed 15mo, NZ	0.33	0.45	0.39		
3	Mixed 21mo, NZ	0.16	0.24	0.32		
Live weight- phenotypic						
1	HF 2yo, NZ	0.18	0.22	0.20	-0.03	0.04
1	J 2yo, NZ	0.19	0.22	0.20	-0.01	0.04
2	Mixed 2yo, NZ	0.24	0.30	0.25	-	-
3	Mixed 9mo, NZ	0.28	0.31	0.32		
3	Mixed 15mo, NZ	0.31	0.36	0.37		
3	Mixed 21mo, NZ	0.30	0.34	0.38		

1 is Ahlborn and Dempfle (1992), 2 is Pryce and Harris (2006), 3 is van der Waaij et al. (1997)

Table 1.6 Heritability estimates of live weight (LWT) in dairy cattle.

Source	Breed and Country	Age	Heritability
Yearling LWT			
van der Waaij et al. (1997)	Mixed, NZ	9 months	0.39
van der Waaij et al. (1997)	Mixed, NZ	15 months	0.52
van der Waaij et al. (1997)	Mixed, NZ	21 months	0.62
Cow LWT			
Haile-Mariam et al. (2014)	HF, Aus	2 years old	0.43
Ahlborn and Dempfle (1992)	Jersey, NZ	2 years old	0.16
Ahlborn and Dempfle (1992)	HF, NZ	2 years old	0.24
Pryce and Harris (2006)	HF, J and Crosses, NZ	2 years old	0.39
Veerkamp et al. (2000)	Unknown, Netherlands	1st Lactation – average LWT over 15 weeks	0.61
Veerkamp et al. (2000)	Unknown, Netherlands	1st Lactation – 1st week of lactation	0.48
Veerkamp et al. (2000)	Unknown, Netherlands	1st Lactation – 15th week of lactation	0.56

Due to a large proportion of two-year-old LWT compared with mature cow LWT records entering the national database; a model was formed to "scale up" LWT from cows aged five years and younger to mature equivalents (DairyNZ 2015b). The mature equivalent LWT are then run through the animal evaluation model to calculate LWT BVs (DairyNZ 2015b). This change was implemented in February 2015, resulting in smaller LWT BVs of Jerseys and their crosses and larger LWT BVs of Friesians and their crosses (DairyNZ 2015b).

As well as being a contributor to BW, LWT BVs have also been used to predict mature LWT of dairy heifers (Bryant et al. 2004). The predicted mature LWT of a heifer can be calculated relative to a group of base animals (Bryant et al. 2004). In the study by Bryant et al. (2004) mature LWT was calculated as 529.3 kg + (LWT BV – 50.6 kg); where 50.6 kg was the average LWT BV of 6-8 year old Holstein Friesian cows that were on average 529.3 kg. DairyNZ recommends adding 500 kg to the average LWT BV of a line of heifers to predict mature LWT (DairyNZ 2018g). This estimate of mature LWT can be used to calculate target LWT at specific ages, which will be discussed below (Section 1.2.3).

However, the phenotypic LWT of the 21,585 genetic base cows (born 2005) was approximately 475 kg (Jeremy Bryant, New Zealand Animal Evaluation 2017). There are no published studies that report the relationships between heifer LWT, LWT BVs and mature LWT in the New Zealand system. It has been assumed that the genetic base cows that were weighed were themselves undergrown which is why 500 kg is used as the base instead of 475 kg (Jeremy Bryant, New Zealand Animal Evaluation 2017).

1.2.3 Target liveweights for NZ dairy heifers

Liveweight-for-age targets for New Zealand Jersey cattle were first suggested by McMeekan (1954) based on “good” growth of heifers at the Ruakura Animal Research Station. The targets suggested were 132 kg at 6 months of age, 229 kg at 15 months of age and 333 kg at calving (24 months) for Jersey cattle, and it was proposed that for Friesians it should be increased by “around 40%” (McMeekan 1954). These suggested targets were based on the growth of Jersey heifers that calved between 700 and 740 pounds of LWT (318 - 336 kg) and produced on average 30 pounds (13.6 kg) more butterfat compared with heifers that weighed between 600 and 650 pounds (272 – 295 kg) at calving. The advantage of the heavier heifers was continued in the second lactation at an average of 20 pounds (9.1 kg) of butterfat (McMeekan 1954).

Target LWT were further developed as minimum targets at different ages for New Zealand Jersey and Friesian heifers (Holmes et al. 1987). These targets were revised by Holmes et al. (2007a) and are reported alongside those from Holmes et al. (1987) in Table 1.7. The target LWT from Holmes et al. (1987) were minimum targets that all heifers need to be above and therefore, are lighter than the targets suggested by McMeekan (1954), which were targets that all heifers should achieve and not necessarily exceed. The target LWTs from Holmes et al. (2007a) were lighter at six months of age, similar at 15 months of age and heavier at calving than those suggested by McMeekan (1954).

Table 1.7 The minimum target liveweights for Jersey and Friesian heifers. Modified from Holmes et al. (1987) and Holmes et al. (2007a).

Age	Jersey minimum target (kg) 1987	Jersey minimum target (kg) 2007	Friesian minimum target (kg) 1987	Friesian minimum target (kg) 2007
Birth	25	25	35	35
Weaning (8-10 weeks)	55	65 - 75	70	80 – 90
6 months	90	110	120	135
12 months	170	190	220	235
15 months	210	230	280	285
18 months	240	270	310	335
24 months (pre-calving)	320	400	420	490
24 months (post-calving)	-	355	-	435

A French study on the effects of winter feeding on the performance of Friesian heifers born in autumn from 1974 to 1978 provided recommended target LWT (Troccon 1993). These target LWT were described as a percentage of expected mature LWT of the heifers (Troccon 1993). The recommended LWT-for-age targets were 30% of mature LWT at 6 months of age, 60% at artificial insemination (A.I) or 15 months of age and 90% at first calving (24 months of age) (Troccon 1993). The targets from Troccon (1993) can be applied to any heifer as long as there is an estimate of mature LWT. The targets mentioned previously by McMeekan (1954) and Holmes et al. (1987) were based on breed average LWT so could not be used for other breeds or crosses such as Ayrshire or Holstein-Friesian-Jersey crossbreds and do not allow for variation of mature LWT within the breeds.

A New Zealand study on Friesian and Jersey heifers designed to quantify the benefits from better-reared heifers concluded that the targets provided by Troccon (1993) “appeared sound in a New Zealand system” (Penno 1997). Within each breed, heifers were split into one of three groups: high (H1), medium (M1) or low (L1) growth from weaning until 200 kg (Friesian) or 165 kg (Jersey), followed by either high (H2) or low (L2) growth rates until 22 months of age, thereby, creating six groups for each breed (Penno 1997). The 60% of mature LWT target at mating corresponded to 300 kg for Friesians and 225 kg for Jerseys; when the average mature LWT was defined as 500 kg and 375 kg for Friesians and Jerseys, respectively (Penno 1997). For both breeds at LWT below 60% of maturity, less than 90% of heifers were cycling (Table 1.8). Interestingly, at 60% of mature LWT 100% of M1L2 Jersey heifers were cycling but at the same percentage of mature LWT only 91% of H1L1 Friesian heifers were cycling.

Table 1.8 Live weight (LWT), cycling activity and estimated percentage of maturity at 15 months of age of Friesian and Jersey heifers. Modified from Penno (1997) with mature LWTs of 500 kg and 375 kg for Friesian and Jersey, respectively.

	H1H2	H1L2	M1H2	M1L2	L1H2	L1L2
Friesian						
LWT (kg)	340	301	314	279	270	252
Proportion cycling (%)	91%	91%	93%	89%	83%	81%
Estimated % of mature LWT	68%	60%	63%	56%	54%	50%
Jersey						
LWT (kg)	255	232	225	224	190	178
Proportion cycling (%)	100%	100%	94%	100%	80%	80%
Estimated % of mature LWT	68%	62%	60%	60%	51%	47%

H=high growth, M=medium growth and L=low growth during Period 1 or 2 where Period 1 was between 100 and 200 kg (Friesian) or 80 and 165 kg (Jersey) and Period 2 was between 200 kg (Friesian) or 165 kg (Jersey) and 22 months of age.

Mature LWT is considered to be reached between six and eight years of age (DairyNZ 2015a). In the study by Penno (1997) the oldest Jersey heifers were born in the spring of 1994 (Penno 1997); and were three years old at the time of publishing, not at mature LWT. The oldest Friesian heifers were born in the spring of 1992 and were five years old at the time of publishing; also, not at mature LWT. Further results from the same animals were published by Macdonald et al. (2005). Liveweights were reported for up to four years of age (51 months of age) and for the Jersey heifers were between 345 – 363 kg (Macdonald et al. 2005), which is less than the reported 375 kg "mature LWT" reported by Penno (1997). It is likely that the mature LWT reported by Penno (1997) was an estimate which could have been provided by LWT BVs or the average mature LWT of the cows on the farms where the heifers were obtained from. Regardless, the conclusion that the target LWT provided by Troccon (1993) were suitable in a New Zealand system are not completely justified in the absence of mature LWT data.

New Zealand Dairy Statistics publish the average LWT of cows at different ages; four-year-old Jersey cows (born in the same year as the aforementioned study) were on average 371 kg (Livestock Improvement Corporation 1999). The average mature LWT of the same birth-year Jersey cows was 412 kg; 41 kg heavier than the four-year-old averages (Livestock Improvement Corporation 1999, 2001, 2002, 2003). Using the same difference of 41 kg from four-years-old to maturity, the Jerseys from Macdonald et al. (2005) would have on average weighed between 386 and 404 kg mature LWT (Table 1.9); heavier than 375 kg reported by Penno (1997). By repeating the same steps for the Friesian heifers, the difference between four-year-old and mature LWT in

Friesian cows was 30 kg (Livestock Improvement Corporation 1997, 1999, 2000, 2001). Using the four-year-old LWT published by Macdonald et al. (2005), the average mature LWT would have been between 469 and 491 kg (Table 1.9); lighter than the 500 kg mature LWT reported by Penno (1997).

Table 1.9 Live weight (LWT) and cycling activity of Friesian and Jersey heifers at 15 months of age, LWT at four years of age and expected mature LWT. Modified from MacDonald et al. (2005).

	H1	M1	L1	H2	L2
Friesian					
LWT at 15 months (kg)	347	323	281	326	308
Proportion cycling (%)	100%	98%	81%	-	-
LWT at 4yo (kg)	461	450	439	452	448
Predicted mature LWT (dairy statistics)	491	480	469	482	478
Percentage of 500 kg LWT at 15 mths	69%	65%	56%	65%	61%
Percentage of mature LWT at 15 mths	71%	67%	60%	68%	64%
Jersey					
LWT at 15 months (kg)	256	240	210	243	227
Proportion cycling (%)	98%	96%	68%	-	-
LWT at 4yo (kg)	363	358	345	359	352
Predicted mature LWT (dairy statistics)	404	399	386	400	393
Percentage of 375 kg LWT at 15 mths	68%	64%	56%	65%	61%
Percentage of mature LWT at 15 mths	63%	60%	54%	61%	58%

H=high growth, M=medium growth and L=low growth during Period 1 or 2 where Period 1 was between 100 and 200 kg (Friesian) or 80 and 165 kg (Jersey) and Period 2 was between 200 kg (Friesian) or 165 kg (Jersey) and 22 months of age.

As the predicted mature LWT for Friesians were lighter than the 500 kg reported by Penno (1997), the percentage of mature LWT was greater and for all groups was above the 60% target LWT (Table 1.9). The opposite occurred for Jersey heifers, two out of the five groups were below the 60% of mature LWT target. It is of interest to note that the cycling results reported by Penno (1997) in Table 1.8 appear to be different to those reported by Macdonald et al. (2005) in Table 1.9. All of the Jersey heifers in the H1H2 and H1L2 groups were cycling at 15 months (Penno 1997), conversely, Macdonald et al. (2005) reported that 98% of Jersey heifers in the H1 group were cycling at 15 months of age.

As previously mentioned (Section 1.2), differences between animals at younger ages were reflective of mature LWT; either due to genetic potential or early-in-life growth restricting the actual mature LWT attained. The LWT differences among treatments in the study by Macdonald et al. (2005) remained until the cows were at least four years of age (Table 1.9); the heifers reared to achieve a high growth rate prior to first calving were heavier at four years of age compared with heifers that were on a low growth rate. The results from the study by Macdonald et al. (2005) provides further evidence that LWT and growth rates prior to first calving has carryover effects on LWT and growth during lactation and potentially mature LWT. As mentioned previously, LWT BVs have been used to predict mature LWT of dairy heifers, and hence target LWT (Bryant et al. 2004). DairyNZ recommends adding 500 kg to the average LWT BV of a line of heifers to predict mature LWT (DairyNZ 2018g). Using the targets from Troccon (1993), target LWT for heifers can be calculated as:

$$(500\ kg + LWT\ BV) \times target\ as\ a\ percentage.$$

These targets have been further broken down to 20% at three, 40% at nine, 50% at 12, 73% at 18, 86% at 21 and 90% at 22 months of age (DairyNZ 2018h). Target growth rates are calculated by taking the difference between the two targets and dividing by the number of days between, thereby creating a mostly linear planned trajectory of growth from three to 22 months of age. For example, for a heifer with an expected mature LWT of 450 kg (LWT BV = -50 kg), her target LWT and growth rates are depicted in Table 1.10 below.

Table 1.10 Liveweight (LWT) and growth rate targets for a heifer aged between three and 22 months with an expected mature LWT of 450 kg.

Age (months)	Target (%)	Target LWT (kg)	Target growth rate (kg/d)
3	20%	90	
6	30%	135	0.5
9	40%	180	0.5
12	50%	225	0.5
15	60%	270	0.5
18	73%	329	0.6
21	86%	387	0.6
22	90%	405	0.6

Bryant et al. (2004) developed a growth model using LWT BVs that accounts for birth weight, mature LWT and growth of foetal components. The model is comparable to the 30, 60, 90% targets (Bryant et al. 2004). A modified version is currently embedded in LIC's MINDA Weights™ herd-recording software to be used by farmers and graziers to monitor heifer growth (Handcock et al. 2016; McNaughton & Lopdell 2013).

Positive heterosis for mature LWT has been reported in F×J cattle and ranged from 7.2 kg to 10 kg (Harris 2005; Harris et al. 1996). It would be expected that growing F×J heifers would also exhibit heterosis for LWT, although there are no estimates in the literature. Production values (PVs) are an estimate of an animal's future production. It is defined as the BV with the addition of non-additive genetic effect, permanent environmental effect and average heterosis effects (Harris et al. 1996). Consequently, PVs measure the “lifetime producing ability of the cow” and not the genetics she passes on to her progeny; which is what BVs measure. McNaughton and Lopdell (2013) recommended that when setting target LWTs for crossbred animals the use of LWT PVs, instead of LWT BVs would provide a more accurate estimate of mature LWT as PVs are able to capture heterosis effects.

1.2.3.2 International target liveweights

In contrast to the New Zealand seasonal dairy system, the Northern Hemisphere system is not strictly seasonal. Cows are kept indoors for large portions of the year and can calve all year round (Mwansa & Peterson 1998). Cows are typically fed high-energy diets made up of concentrates and conserved forages (Mwansa & Peterson 1998). Dairy cattle in the Northern Hemisphere are generally heavier than New Zealand cattle, so require faster growth rates throughout the rearing period (Macdonald et al. 2007).

The main goals of rearing dairy heifers in this system are to grow heifers at an adequate rate to enable them to breed and calve between 22 and 24 months of age, to optimise economic returns (Akins 2016; Ettema & Santos 2004; Hutchison et al. 2017; Le Cozler et al. 2008; Wathes et al. 2014). The cost to rear heifers makes up approximately 25% of a Northern Hemisphere dairy farm’s production costs, with feed comprising 54% of these costs (Akins 2016).

The target LWT for dairy heifers in the United Kingdom are similar to those for New Zealand dairy heifers of 55 – 60% of mature LWT at mating, and 85 – 90% at first calving (Wathes et al. 2014). The target LWT of dairy heifers in North America are 55%, 94% and 85% of mature LWT at breeding, pre-calving and post-calving, respectively (Akins 2016). These targets are inclusive of conceptus weight gain over the duration of pregnancy (Akins 2016). To estimate mature LWT of a heifer, Hoffman (2007) recommended to multiply the heifer’s dam’s 0- to 21-day post-calving LWT by an adjustment factor. For first, second or third lactation cows the adjustment factors were

1.176, 1.087 or 1.042, respectively. Interestingly, multiplying by these adjustment factors equates to 85%, 92% and 96% of mature LWT after first, second and third calving, respectively. For dams in their fourth lactation and older no adjustment factor is necessary (Hoffman 2007). Hence in the North American dairy system, cows are assumed to have attained mature LWT by their fourth calving. In the New Zealand system, there are no target LWTs for heifers after their first calving, the focus turns to reproductive performance targets and milk production.

Although North American cows are heavier than New Zealand cows, the North American target LWTs for a heifer with an expected mature LWT of 450 kg are depicted in Table 1.11 for comparison with the New Zealand targets in Table 1.10. Target growth rates are calculated the same way as for New Zealand heifers, by linear interpolation (Akins 2016; Hoffman 2007).

Table 1.11 North American liveweight (LWT) targets for a heifer between first breeding and fourth calving with an expected mature LWT of 450 kg.

Milestone	Target (%)	Target LWT (kg)	LWT x adjustment factor
Breeding	55%	248	
Pre-calving	94%	423	
Post-calving (first)	85%	383	383*1.176 ~450 kg
Post-calving (second)	92%	414	414*1.087 ~450 kg
Post-calving (third)	96%	432	432*1.042 ~450 kg
Post-calving (fourth)	100%	450	

1.3 Reproduction

In order to be a successful cow, a heifer must develop follicles, commence oestrous cycles, become pregnant and have a successful birth. Once she has begun to lactate she must continue the cycle all over again. Failure or delay to do any of these would affect reproductive success. As a 365-day calving interval is important in the New Zealand system, there is only a small window where a cow must conceive, or she will be culled.

1.3.1 Puberty

Puberty is defined as the completion of the gradual maturation process that results in an ovulation accompanied by oestrus and normal luteal function (Amstalden et al. 2014; Byerley et al. 1987; Larson 2007; Sejrsen 1994; Velazquez et al. 2008). Ovulation, oestrus and normal luteal function are considered together rather than apart due to; the first ovulation may not be followed by an observable oestrus (Berardinelli et al. 1979; Swanson et al. 1972), behavioural oestrus can occur without ovulation (Nelsen et al. 1985; Swanson et al. 1972) and a period of elevated progesterone (indicative of ovarian luteal tissue, but not necessarily due to an ovulation) often occurs prior to puberty (Berardinelli et al. 1979; Gonzalez-Padilla et al. 1975). In the New Zealand seasonal dairy production system, it is required that heifers conceive at 13 to 15 months of age in order to calve at 22 to 24 months of age (Holmes et al. 2007a; McNaughton et al. 2002). The conception rate of beef heifers bred to their third oestrus was greater compared with heifers bred to their first oestrus (Byerley et al. 1987), therefore, the early onset of puberty is advantageous.

The hypothalamic-pituitary-gonadal (HPG) axis; made up of the hypothalamus, pituitary gland and the gonads (ovary in female) provides the main control of reproductive functions in the heifer (Whirledge & Cidlowski 2010). The hypothalamus secretes gonadotropin releasing hormone (GnRH), which binds to receptors in the anterior pituitary to stimulate the synthesis and release of luteinising hormone (LH) and follicle stimulating hormone (FSH) (Whirledge & Cidlowski 2010; Whittier et al. 2008). In the ovary, LH stimulates oocyte maturation, ovulation and the formation of the corpus luteum (CL) (Whirledge & Cidlowski 2010; Whittier et al. 2008). Follicle stimulating hormone stimulates follicular cell growth and oestradiol production (Whirledge & Cidlowski 2010).

1.3.1.1 Live weight and growth rate effects on puberty attainment

A factor that determines the timing of puberty is genetics; however, different environmental factors may modify the onset of puberty (Roa et al. 2010). The heritability of age at puberty in beef heifers (bos taurus) has been reported to be between 0.07 – 0.67 (Martin et al. 1992; Morris et al. 1993; Morris et al. 2000) and between 0.13 and 0.76 in New Zealand dairy heifers (Price et al. 2017). Nutrition through its effect on LWT and growth rate is a major factor for the variation in age at onset of puberty in heifers (Chelikani et al. 2003; Gardner et al. 1977; Sejrsen 1994). The amount of energy reserves is also a key factor that determines the onset of puberty in mammals (Roa et al. 2010). Sixty percent of heifers were reported to be pubertal at the start of a heifer synchrony programme study (McDougall et al. 2013). In that study, more heifers with a BCS greater than 4.5 were pubertal than heifers with a BCS less than

4.5 (McDougall et al. 2013). These studies indicate that reproductive development in cattle may be more closely related to body development than to chronological age (Larson 2007; Sejrsen 1994).

The onset of puberty occurs at approximately 49% mature LWT (Table 1.12) and is more closely related to LWT rather than age (Freetly et al. 2011). Beef heifers gaining 1 kg/day post-weaning reached puberty earlier than heifers gaining 0.4 kg/day (Buskirk et al. 1995). Similarly, Holstein heifers fed to achieve 1.0 kg/day attained puberty at similar LWT, but 32 days earlier, than those fed to achieve 0.7 kg/day (Lammers et al. 1999). Furthermore, Le Cozler et al. (2009) reported that puberty occurred at similar LWT but different ages in Holstein heifers grown at different trajectories between four and 12 months of age. In addition, more Friesian heifers that were heavier (>291 kg) at 15 months of age were pubertal at mating start date compared with heifers that were lighter (<290 kg) (Archbold et al. 2012).

In contrast, Little et al. (1981) reported that 23% of the variation in LWT at puberty could be explained by LWT gain prior to puberty, with the fastest growing heifers reaching puberty at similar ages but greater LWTs than the slower growing heifers. Likewise, Short and Bellows (1971) reported that as winter feeding level increased, the LWT at which beef heifers reached puberty also increased. Similarly, a study on nutrition in the pre-weaning period demonstrated that Holstein heifer calves fed an intensive milk replacer diet were younger and lighter at the onset of puberty compared with those fed a conventional diet (Davis Rincker et al. 2011). These studies indicate that although puberty attainment is related closely with LWT, nutrition and growth trajectory also have significant impacts. Table 1.12 details the age, LWT and percentage of mature LWT when puberty was attained. The average age and LWT at puberty attainment were 354 and 332 days and 260 and 182 kg for Holsten-Friesian and Jersey heifers, respectively (Table 1.12).

Table 1.12 Age, live weight (LWT), mature LWT and percentage of mature LWT (maturity) when puberty was attained for Holstein-Friesian, Jersey and Holstein-Friesian-Jersey crossbred heifers.

Breed, source, country and description	Age (days)	LWT (kg)	Mature LWT (kg)	Maturity (%)
Holstein-Friesian (F)				
McNaughton et al. (2002) (NZ vs OS genetics over two years)	356	253	540[1]	47%
	380	258	540[1]	48%
	329	230	540[1]	43%
	381	237	540[1]	44%
	373	274	640[1]	43%
	374	271	640[1]	42%
Garcia-Muniz (1998) (NZ heavy vs light)	325	241	504	48%
	300	221	467	47%
Hickson et al. (2011) (NZ)	364	265	497[2]	53%
Macdonald et al. (2005) (NZ high, medium and low growth rates)	355	251	461[3]	54%
	383	251	450[3]	56%
	419	251	439[3]	57%
Meier et al. (2017) (NZ high and low fertility)	358	271	535[1]	51%
	379	296	538[1]	55%
Lammers et al. (1999) (USA medium and high growth rates)	334	294	622[4]	47%
	311	306	621[4]	49%
Swanson et al. (1972) (USA)	303	253	-	-
Jersey (J)				
Hickson et al. (2011) (NZ)	294	189	421[5]	45%
Macdonald et al. (2005) (NZ high, medium and low growth rates)	291	180	363[3]	50%
	344	180	358[3]	50%
	398	180	345[3]	52%
Holstein-Friesian and Jersey crossbreeds				
Hickson et al. (2011) (NZ; F x Angus, J x Angus and FxJ x Angus)	388	274	-	-
	383	242	-	-
	385	263	-	-
Morris et al. (1986) [NZ F x (Hereford or Angus)]	377	249	-	-
Morris et al. (1986) [NZ J x (Hereford or Angus)]	339	206	-	-

[1]Estimated based on LWT breeding values.
[2]Expected based on average of 2008 born Holstein-Friesians (Livestock Improvement Corporation & DairyNZ 2015).
[3]Based on LWT at four years of age.
[4]Based on LWT during first lactation.
[5]Expected based on average of 2008 born Jerseys (Livestock Improvement Corporation & DairyNZ 2015).

1.3.2 Pregnancy and parturition

1.3.2.1 Oestrous cycles

Oestrous cycles of cattle are typically 21 days long (Byerley et al. 1987; Swanson et al. 1972), but can range from 9 to 56 days (Byerley et al. 1987; Swanson et al. 1972). Oestrous cycles commence at puberty and occur at regular intervals throughout the cow's lifetime, apart from during pregnancy and immediately following parturition.

The follicular period of the oestrous cycle starts with GnRH stimulating a release of FSH which causes the dominant follicle to mature (Ball & Peters 2004). The dominant follicle produces oestrogen that induces oestrus behaviour and positive feedback on the hypothalamus to release further GnRH (Ball & Peters 2004). The GnRH stimulates the release of LH which causes ovulation of the dominant follicle, which is the start of the luteal period. The CL is formed from the ovulated follicle and secretes progesterone (Bazer 2013). In non-pregnant cattle after approximately 17 days the release of prostaglandin $F_{2\alpha}$ from uterine epithelia results in the regression of the CL and a decline in progesterone secretion (Bazer 2013). The decline in progesterone signals the release of GnRH from the hypothalamus and LH from the pituitary to induce ovulation and commence a new oestrous cycle (Ball & Peters 2004; D'Occhio et al. 1999).

1.3.2.2 Pregnancy

If the ovulated oocyte is fertilised and pregnancy is successful, the resulting zygote migrates to the uterine horn and begins to differentiate into placental and foetal cells (conceptus). By day 50 of gestation, the majority of the foetal calf's features are present, after which the majority of development is growth and maturation of the organs and structures of the calf. Therefore, the first three months of gestation are critical for development of the foetus (Long et al. 2009).

The gestation length (period from conception until parturition) in dairy cattle is approximately 282 days (Donkersloot 2014; Haile-Mariam & Pryce 2019). Gestation length is longer in cows carrying male calves compared with female calves (Donkersloot 2014), and for two-year-old cows compared with older cows (Donkersloot 2014; Haile-Mariam & Pryce 2019). Pregnancy is maintained by the presence of the CL secreting progesterone (Thorburn et al. 1977). From approximately day 120, non-ovarian sources of progesterone in addition to the CL's progesterone maintain pregnancy until the last few weeks of pregnancy when only the CL is secreting progesterone (Thorburn et al. 1977).

The growth of the foetus occurs exponentially throughout pregnancy (Prior & Laster 1979); therefore, the nutrient requirements of the growing conceptus are very small for the first two-thirds of gestation and increase rapidly in the final third. The supply of nutrients to the foetus is usually maintained even if the cow's intake is restricted as the growing foetus has a high priority for nutrients (Prior & Laster 1979). In cases where the cow's intake is greatly restricted, nutrients will be mobilised from body reserves to support foetal growth, resulting in loss of LWT of the cow. Furthermore, Thomson et al. (1991) reported that the LWT gain of first-calving heifers in the three months prior to calving was 8 kg, compared with 33 kg for mature cows when heifers and mature cows were grazed together before the heifers first calving. As is common in the seasonal pasture-based system, this coincided with the period when heifers returned from a heifer rearing facility to the milking farm, were introduced to the herd and the nutrient requirements for foetal growth increased exponentially.

Initiation of parturition is primarily under control of the foetus. Following the birth of the calf comes the expulsion of the placenta (usually 4 to 5 hours after birth) (Laven & Peters 1996). Occasionally, the placenta (or parts of it) remains attached which is termed "retained placenta" and is a major cause of metritis (infection and inflammation of the uterus) which can lead to anoestrus and other fertility issues (Laven & Peters 1996) (as discussed in Section 1.3.3).

A New Zealand study of naturally mated heifers reported that 92.7% of heifers that were mated (n=7,053), successfully calved as two-year-olds (MacMillan 1994). A greater proportion of replacement heifers that calved early (within 21 days of first PSC) in their first lactation also calved early (within 42 days of second PSC) in their second lactation compared with heifers that calved later (after 21 days from first PSC) in their first lactation (Pryce et al. 2007). This relationship between earliness of calving in subsequent years emphasises the importance of early calving heifers, as they are likely to become early calving cows. Therefore, factors affecting the likelihood of achieving a successful, early pregnancy and calving are important to the farming system.

1.3.2.3 Liveweight and growth rate effects on pregnancy and parturition

In many dairy farms, heifers are not recorded as "herd members" until just prior to or just after their first calving. In addition, the majority of 15-month-old heifers are naturally mated to bulls, with the dates of mating either not recorded or poorly recorded. Therefore, the reproductive performance of first calving/maiden heifers is often poorly understood and the majority of studies present calving data rather than pregnancy data.

Byerley et al. (1987) reported that fertility improves over the first few oestrous cycles and Johnsson and Obst (1984) reported that heifers that attained similar LWT at mating but had different proportions pubertal (81 vs 75%) resulted in differences in calving rate (85 vs 75%). However, beef heifers grown to 55% of mature LWT at breeding were older at puberty but had a similar proportion pregnant compared with heifers grown to 62% of mature LWT (Lardner et al. 2014). In Holstein-Friesian heifers from the USA, and in New Zealand dairy and dairy-beef crossbred heifers, there was no evidence to suggest that age at puberty was associated with the speed at which heifers conceived (Hawk et al. 1954; Hickson et al. 2011). Similarly, Macdonald et al. (2005) reported that the proportion of heifers cycling at mating start date was associated with growth rate pre-puberty, in that more faster growing heifers were cycling compared with slower growing heifers. Despite the large differences in LWT and proportion cycling, there was no effect on pregnancy rates after a 10-week breeding period (Macdonald et al. 2005). However, oestrus was synchronised at 15 months of age for all heifers in the study by Macdonald et al. (2005); therefore, it was not possible to tell what impact the delayed onset of oestrus for the slower growing heifers may have had on final reproductive performance.

Similarly, Ducker et al. (1982) reported that there were no differences in reproductive success in heifers grown in differing planes of nutrition. Despite this, within each plane of nutrition group, there were differences in fertility (Ducker et al. 1982); heifers with the most severe response to the change from a high to a low plane of nutrition (lost the most BCS/LWT), were less fertile than those within the same treatment that were better able to maintain BCS/LWT. Likewise, heifers that had a greater increase in BCS/LWT when switched from a low to a high plane of nutrition were more fertile compared with heifers that did not have as a great a response to a change in nutrition. In addition, Roberts et al. (2016) reported that for their 10-year study, there were no differences in pregnancy rates for beef heifers grown in a restricted (0.52 kg/d) or control (0.67 kg/d) treatment for 140 days after weaning, despite differences in LWT at the start of breeding (305 kg vs 322 kg for restricted and control, respectively). These studies indicated that LWT and growth prior to first breeding did not affect pregnancy rates of heifers. However, in the studies by Ducker et al. (1982) and Macdonald et al. (2005), all heifers were synchronised for oestrus prior to mating start, so it was not known what effect this may have had on pregnancy rates.

In contrast, LWT at first mating was associated with earliness of first calving (Archbold et al. 2012; McNaughton & Lopdell 2013). McNaughton and Lopdell (2013) found a significant curvilinear relationship between target LWT at PSM and calving date relative to PSC, in that heifers that were further from target LWT (below and above) calved later compared with heifers that were closer to target LWT. Furthermore, Holstein-Friesian heifers that were heavier at first mating had an earlier mean date of first calving compared with heifers that were lighter at first calving (Archbold et al. 2012). This relationship was not continued into second or third calving dates (Archbold et al. 2012); however, more of the heavier Holstein-Friesian heifers were present at the beginning of first (93% vs 82%) and second (76% vs 62%) lactation compared with the lighter heifers (Archbold et al. 2012), demonstrating that although LWT may not have had an impact of earliness of calving in later years, it did have a positive impact on probability of calving. Vargas et al. (1998) reported a significant effect of heifer LWT on age at first calving and probability of calving for Holstein, Jersey and other breeds. Heifers that were heavier at 390 d (approximately 13 months of age) had a higher probability of calving compared with heifers that were lighter at the same age (Vargas et al. 1998). Results from Vargas et al. (1998) provided further evidence that there may be a relationship between heifer LWT and probability of calving.

Live weight at 180 and 450 days of age (approximately six and 15 months of age) was significantly associated with age at first calving in British Holstein-Friesian heifers (Brickell et al. 2009a). Heavier heifers were younger at first calving compared with lighter heifers (Brickell et al. 2009a). In addition, increased growth rate between 180 and 450 days of age was associated with a reduced age at first calving (Brickell et al. 2009a). However, Brickell et al. (2009a) reported that there was a trend ($P<0.1$) for heifers that failed to conceive to be heavier at 450 days of age compared with those that did conceive (391 vs 368 kg). These results should be interpreted with caution due to the low number (n= 16 out of 428; 3.7%) of heifers that failed to conceive in the study by Brickell et al. (2009a).

Body condition score has been reported to explain 12 to 45% of the genetic variation in LWT of Holstein-Friesian cattle (Veerkamp & Brotherstone 1997). Similarly, there was a positive correlation between LWT and BCS at calving in New Zealand Jersey and Holstein-Friesian cattle (Roche et al. 2007). Ferrell (1982) reported that heifer BCS had a curvilinear relationship with pregnancy rates of beef heifers. Ferrell (1982) determined that a BCS of 6.7 (on a 1 to 9 scale) was optimum for pregnancy rate, and that excessively thin and excessively fat heifers were at risk of having lower pregnancy rates compared with moderately conditioned heifers. Furthermore, differences in oocyte quality were reported in a study of Scottish dairy x beef heifers of low or moderate BCS that were fed either once or twice maintenance requirements (Adamiak et al. 2005). Heifers of low BCS benefitted from a high level of feeding, whereas, a high level of feeding to heifers of moderate BCS was detrimental to oocyte quality (Adamiak et al. 2005). However, the study by Adamiak et al. (2005) was of heifers fed a concentrate-based diet, and the authors postulated that a possible mechanism for the reduction in oocyte quality was due to a high level of concentrate feeding to the moderately fat heifers causing hyperinsulinemia. Therefore, application of the results from Adamiak et al. (2005) to heifers in pasture-based systems should be treated with caution due to differences in dietary composition between the systems.

1.3.3 Postpartum anoestrus

After parturition, cows experience a period during which oestrus and ovulation do not occur. The period from parturition to first oestrus is the postpartum anoestrus interval (PPAI), the period from parturition to first ovulation is termed the postpartum anovulatory interval. Direct comparisons between postpartum anoestrus and postpartum anovulatory intervals are not appropriate due to first ovulation often not being accompanied by behavioural oestrus (similar to first ovulation pre-puberty; Section 1.3.1). McDougall et al. (1995) and Fonseca et al. (1983) reported that the PPAI for Jerseys were shorter than for Friesians. In addition, two-year-olds had PPAI of 47.1 days, approximately nine days longer than for three-year-olds (38.4 days) and approximately 15 days longer than cows older than three (32.5 days). Similar relationships existed for interval from calving to first ovulation (McDougall et al. 1995). The longer PPAI of first-calving heifers often leads to the practice of mating 15-month-old heifers one- to two-weeks earlier than the main herd, so that they are cycling at a similar time to their older herdmates.

In a seasonal calving system where the 365-day calving interval is important, a 282-day gestation period leaves approximately 83 days for the cow to conceive again after giving birth. With the average PPAI being 32 days for cows older than three years of age (McDougall et al. 1995), this leaves only two to three possible oestrous cycles, so two to three opportunities to get pregnant in order to calve at the same time the next year. As mentioned previously, mating begins on a fixed calendar date in a seasonal calving herd, so for later-calving cows the interval between calving and mating start date is shorter, leading to many cows being mated on their first oestrus. Similar to conception rates near puberty, conception rates increase with each additional oestrous cycle (Butler 2000). Therefore, it is advantageous to have cows cycling as early as possible after calving to allow more for oestrous cycles before PSM.

1.3.3.1 Liveweight and growth effects on PPAI

It is well reported that milk production and reproduction are negatively associated (Berry et al. 2003; Grosshans et al. 1997), in that cattle that are producing more milk are more likely to have reduced fertility. The majority of cows enter a state of negative energy balance after calving; negative energy balance is the term used for when the energy expended by the cow in order to produce milk in early lactation is greater than the energy she can consume from her diet (Butler 2000). This occurs in early lactation, when milk yield is peaking, and feed quality may not be high enough to support these milk yields. Furthermore, high-yielding cows have better ability to mobilise fat and muscle to support high milk production and hence are more likely to be in a more severe negative energy balance compared with a lower yielding cow (Wathes et al. 2007). In addition, cows that have higher BCS at calving have more BCS available to mobilise and are also likely to be in a more severe negative energy balance (Butler 2000; Garnsworthy & Topps 2010). As previously mentioned, LWT and BCS are positively correlated, therefore, losses in BCS in early lactation are observable through losses in LWT. A reason for this relationship is that cows that have a large amount of fat reserves are likely to exhibit a decrease in appetite (Garnsworthy & Topps 2010), resulting in increased mobilisation of body stores, which is associated with a longer PPAI (Butler & Smith 1989). Furthermore, beef cows that calved in low body condition (less than 5 on a 1 to 9 scale), had greater intervals from calving to first oestrus compared with beef cows that have BCS greater than 5 (Short et al. 1990; Williams & Amstalden 2010). An increase in supplementation reduced the length of the PPAI in thin cows but not fat cows

(Short et al. 1990). In addition, a low BCS at calving had greater negative effects on reproductive performance than a loss in BCS after calving (Williams & Amstalden 2010).

A New Zealand study by Roche et al. (2007) demonstrated that all of the reproductive measures studied (probability of exhibiting oestrus before mating start, being mated within 21 days of mating start date, pregnant to first mating, or within 21, 42, and 84 days of mating start date) were negatively affected when LWT or BCS during lactation indicated a more severe or longer duration of the negative energy balance after calving. Cows that lost more BCS or LWT from calving to mating start date, were less likely to exhibit oestrus before mating start date compared with cows that did not lose as much BCS or LWT (Roche et al. 2007).

The proportion of beef cows cycling on the first day of the mating season was significantly affected by date of calving (Whittier et al. 2008). More cows had initiated oestrous cycles when they had longer periods of time between calving and the PSM (calved earlier) (Whittier et al. 2008). As mentioned previously, LWT at first mating was associated with earliness of first calving (Archbold et al. 2012; McNaughton & Lopdell 2013). Therefore, it would be expected that heifers that were heavier at first breeding would calve earlier, and thus recommence oestrous cycles earlier than lighter heifers.

1.3.4 Longevity/survival

Poor reproductive performance has been shown to be the main cause of cow removal from herds in New Zealand (35% of cows culled were for reproductive reasons) (Kerslake et al. 2018). Herds that have greater cow survival rates will have a greater proportion of mature, high producing cows and a lower proportion of replacement heifers needing to be reared compared with herds that have low cow survival rates (Pritchard et al. 2013). In addition, if reproductive performance is poor, there is limited ability to cull cows for low production and other undesirable features (e.g. temperament or conformation).

The average number of lactations completed by cows in New Zealand is approximately 4.5 (DairyNZ 2017). Milk production peaks at approximately five years of age, and the animals with the highest genetic merit are two-year-olds; therefore, to balance increasing genetic merit with increased milk production, there is an industry recommended herd age structure from DairyNZ (2017), this is depicted in Table 1.13 below. Based on these recommendations (Table 1.13) the survival rates from each year can be calculated. For example, the proportion of three-year-old cows that were present in the herd as two-year-olds would be 88.9% (16%/18%) and the proportion of four-year-olds that were present in the herd as three-year-olds would be 81.3% (13%/16%). As mentioned previously (Section 1.1.3), between 18-24% of herd tested cows are two years of age (Livestock Improvement Corporation & DairyNZ 2018), greater than the 18% recommended. In addition, based on the herd testing data from Livestock Improvement Corporation and DairyNZ (2018), there were more younger cows than recommended (19, 16 and 13% for 3yo, 4yo and 5yo, respectively) and less older cows than recommended (10, 7, 5, 4 and 4% for 6yo, 7yo, 8yo, 9yo and 10yo+, respectively). This indicates that cow survival to older ages is low and that more heifers are being reared in order to maintain herd numbers.

Table 1.13 Recommended age structure for New Zealand dairy herds and example number (No.) of cows for each age group based on a 500 cow herd. Modified from DairyNZ (2017).

Age	2yo	3yo	4yo	5yo	6yo	7yo	8yo	9yo	10yo +
% of herd	18%	16%	13%	12%	11%	9%	8%	7%	6%
No. of cows in a 500 cow herd	90	80	65	60	55	45	40	35	30

Herds with greater cow survival rates will generally have greater milk production compared with herds that have lower survival rates due to having more of the high producing older cows in the herd (Pritchard et al. 2013). This does not necessarily mean that herds with lower survival rates of cows (and hence have greater numbers of heifers) will have greater genetic merit, as lower survival rates are likely attributed to poor reproductive performance (Kerslake et al. 2018). Therefore, the number of non-pregnant cows are equivalent to the number of replacement heifers available and hence the farmer/herd owner cannot select animals to cull based off of poor milk production or low genetic merit.

There are two types of culling; voluntary and involuntary. Voluntary culling is removal of healthy, fertile cows due to reasons determined by the farmer (Weigel et al. 2003); for example, low milk production or genetic merit. Involuntary culling is the removal of productive cows due to death, disease or failure to get pregnant (Weigel et al. 2003). The majority of non-pregnant cows in New Zealand were involuntarily culled for reproductive failure (Kerslake et al. 2018). The main aim for a pasture-based farmer is to increase the farmers ability to voluntarily cull cows and reduce the amount of involuntary culling (Weigel et al. 2003). One such method would be to increase reproductive performance, as this would enable more cows pregnant to AI, and therefore, likely to produce a high genetic merit heifer calf. Having more cows pregnant also gives more options to the farmer to cull cows based on their herd goals.

Throughout the literature there are various methods to measure survival of production animals (Bach 2011; Brickell & Wathes 2011; Hudson & Van Vleck 1981); these are dependent on what data is available. The most obvious measure of survival is time from birth until death/herd removal. In order to utilise this method accurate dates of birth and removal/death are required. Therefore, smaller datasets on a specific number of herds are recommended so that researchers can closely monitor data recording practices. Following on from survival from birth until removal/death is “productive life”. Productive life is the number of days a cow has spent producing milk and hence income for the farmer (Bach 2011). In addition to accurate recording of birth and death dates, accurate calving and dry-off dates are required in order to get a good estimate of the number of days the cow has spent producing milk in her lifetime. Therefore, smaller, closely monitored datasets or larger datasets where recording of key dates is mandatory are recommended for measuring productive life.

A measure of cow survival that does not require recording of cull data is stayability (STAY); Hudson and Van Vleck (1981) defined STAY as the probability of an animal surviving to a specific age given that they had the opportunity to reach that age. Most studies have the first calving event as the base level (Brickell & Wathes 2011), and express STAY as a binary trait indicating presence or absence at later calving events. A second measure of survival is marginal stayability (MSTAY); it is expressed as the probability of being present at the subsequent calving (n +1), given an animal's presence at a particular calving (n) (McIntyre et al. 2012).

A study in Great Britain revealed that the mean time the costs to rear a heifer were repaid was 530 days (1.5 lactations) before becoming profitable for the farm (Boulton et al. 2017). The study by Boulton et al. (2017) was based off of a mix of year-round and seasonal calving systems and assumed a 305-day lactation each year. It is therefore likely that in the New Zealand system where the average lactation is 274 days (Livestock Improvement Corporation & DairyNZ 2018), the length of time for a heifer to become profitable may be longer than that reported by Boulton et al. (2017) due to less productive days per lactation. However, there are substantial differences between the

British and New Zealand farming systems, additionally, there are no published studies based on the New Zealand system of the time taken to repay the costs of rearing a heifer. Therefore, application of the results from Boulton et al. (2017) should be done so cautiously. Despite this, methods to improve the survival of heifers would be advantageous in order to improve profitability of the farm system.

Several studies based in the United Kingdom reported that between 85.5 to 89% of Holstein-Friesian heifers survived from birth to first calving (Brickell et al. 2009b; Cooke et al. 2013; Pritchard et al. 2013). A New Zealand study on divergent genetic fertility in heifers reported that the loss of Holstein-Friesian heifers from collection (approximately nine days of age) to 17 months of age was 4.8% and 9.8%, for heifers that were of high (n=289) or low (n=276) genetic merit for fertility, respectively (Meier et al. 2017). Further results from these same heifers have been reported by Burke et al. (2018), and the final non-pregnancy rate after the first mating period of 14 weeks was 2% for the high and 6% for the low fertility heifers. Burke et al. (2018) did not report the number of heifers from which the non-pregnancy rate was calculated, but if the final number remaining at 17 months of age reported by Meier et al. (2017) is assumed, this equates to approximately 7% of the high and 15% of the low fertility heifers failing to remain in the herd until first calving (Burke et al. 2018; Meier et al. 2017). In addition, Compton (2018) reported that 23% of heifers were culled (4.4%), sold (15.8%) or died (2.8%) between birth and first calving in New Zealand dairy herds. Reasons for removal included poor conformation, freemartinism, poor health and death (Meier et al. 2017). Reasons for lack of survival from the UK studies were not known, the authors postulated it might be due to illness, trauma or reproductive failure (Pritchard et al. 2013).

There are no targets for stayability/survival of heifers and cows in milking herds, however, Compton (2018) reported that 85.5% of first parity heifers completed their first lactation. Similarly, Livestock Improvement Corporation and DairyNZ (2017) report the "survivability" percentages of each year group; 84.1% of two-year-olds that were milked in the 2015/16 season were milked as three-year-olds in the 2016/17 season. The proportions reported by Compton (2018) and Livestock Improvement Corporation and DairyNZ (2017) provide a benchmark of industry level performance.

1.3.4.2 Liveweight and growth rate effects on survival

Reproductive performance as discussed previously (Section 1.3.2.3 and 1.3.3.1) affects cow survival, because cows that fail to get pregnant will be removed from the herd. Additionally, cows that are due to calve late in the calving period and those that were pregnant but failed to remain pregnant (aborted) also may be removed from the herd (Kerslake et al. 2018). Therefore, LWT and growth rate effects on reproductive performance will also affect cow survival in the herd. Furthermore, poor milk production performance of cows increases the probability of their removal from the herd (Kerslake et al. 2018). Therefore, anything that increases milk production of the cow, not at the expense of reproduction, will increase the chance of survival in the herd. Therefore, LWT through its positive influence on milk production may positively effect cow survival (as will be discussed in Section 1.4.2 below).

Furthermore, the heritability of heifer survival was low (0.01), suggesting that environmental factors influenced heifers' survival to 25 months of age to a greater extent than genetics (Pritchard et al. 2013). A suggestion to improve heifers' survival was to improve the management of heifers (Pritchard et al. 2013), which may result in an improvement in heifer LWTs. More of the heavier Holstein-Friesian heifers were present at the beginning of first (93% vs 82%) and second (76% vs 62%) lactation compared with the lighter heifers (Archbold et al. 2012). Similarly, McNaughton and Lopdell (2013) reported that heifers that did not have any calving recorded were a lower percentage of target LWT (between 15 and 17 months of age) compared with heifers that did have a recorded calving. Likewise, heifers that had only one calving recorded were a lower percentage of target LWT compared with heifers that had two calvings recorded (McNaughton & Lopdell 2013). These studies provide further evidence that there are reproductive and survival benefits of having heifers heavier at mating.

The majority of studies on the effects of growth and growth pattern on survival in dairy cattle focus on preweaning growth or the effects of growth (pre- and postweaning) on puberty or milk production, and not subsequent reproductive performance or survival (Bach 2011; Davis Rincker et al. 2011; Macdonald et al. 2005; Raeth-Knight et al. 2009). For example, Raeth-Knight et al. (2009) reported that Holstein calves fed a high energy and high protein milk replacer diet from three until 56 days of age gained 0.8 kg/d during the preweaning period and calved approximately 27 days younger than calves fed a conventional milk replacer who gained 0.55 kg/d. Macdonald et al. (2005)

reported that growth rate between 100 and 200 kg or 200 kg and 22 months of age for Holstein-Friesian or between 80 and 165 kg or 165 kg and 22 months of age for Jersey heifers had no impact on first calving date, calving interval, or proportion of heifers surviving to second or third lactation. As discussed earlier, all heifers in the study by Macdonald et al. (2005) were synchronised for oestrus prior to mating start which may have influenced the lack of differences among treatments. Despite this, Bach (2011) reported that Holstein heifers that reached second lactation grew more (0.8 kg/d) between 12 and 65 days of age than heifers that did not reach second lactation (0.7 kg/d). Bach (2011) also reported that the effect of growth rate from 12 days of age to first breeding on survivability to second lactation approached significance, but there was no effect of growth rate after breeding on survivability. Results from Bach (2011) indicate that early-in-life growth may be more important to heifer survival compared with later in life growth.

In contrast, Wall et al. (2007) demonstrated that LWT change early in the first lactation was correlated with lifespan; cows that lost less LWT in early lactation were more likely to survive longer in the herd compared with cows that lost a large amount of LWT. The authors postulated that animals that were further from maturity at first calving (i.e. were lighter at first calving) and hence were still growing in early lactation could partition energy towards growth and away from milk production with positive effects on overall survival in the herd (Wall et al. 2007).

1.4 Milk Production

1.4.1 Mammary gland development

After a cow has successfully given birth, she produces milk. In order to produce well, she must have a sufficiently developed mammary gland. Mammary gland development begins in utero with the basic structures fully developed at birth (Lohakare et al. 2012; Rowson et al. 2012). There are two distinct periods of rapid/allometric mammary gland growth; from three months of age until puberty and from the third month of pregnancy until parturition (Rowson et al. 2012; Sejrsen 1994; Sinha & Tucker 1969). Before and between these periods, mammary gland development is at the same rate as the rest of the body (isometric) (Sejrsen 1994; Sinha & Tucker 1969).

In the first allometric phase (pre-puberty), epithelial cells advance into the fat pad by elongation and branching (Rowson et al. 2012). Mammary ducts continue to lengthen towards the boundaries of the fat pad (Rowson et al. 2012). At this point alveoli are not present. At puberty, mammary gland growth slows to the same rate as the rest of the body (isometric) (Rowson et al. 2012; Sejrsen 1994). Although it is at a slower rate, with each oestrous cycle, parenchymal development increases (Tucker 1969). Therefore, it would be advantageous for heifers to have multiple oestrous cycles before becoming pregnant which can be achieved by an earlier onset of puberty.

The second allometric phase (late-pregnancy) consists of mammary parenchyma replacing adipose tissue, followed by the formation of alveolar lobules (Rowson et al. 2012). The ability of the mammary gland to produce milk depends on the number of epithelial cells (parenchyma/secretory tissue), the secretory activity per cell and the volume of the alveoli (Akers et al. 2006). During pregnancy the proportion of area occupied by stroma (connective tissue), epithelium and lumen (alveoli) were one third each (Akers et al. 2006) due to an increase in number and volume of alveoli rather than a disappearance of stromal cells.

As mentioned earlier, the mammary gland must have a period of not lactating (dry period) in order to recover and regenerate before the commencement of the next lactation (Capuco et al. 1997; Holmes et al. 2007b). At dry-off, the mammary gland undergo a regression and involution; tissue remodelling and epithelial regression (Rowson et al. 2012). The initial "active" phase of involution takes approximately 30 days, however because dairy cattle are pregnant during the dry-period, their mammary gland does not fully regress as many alveoli remain in preparation for the next lactation (Rowson et al. 2012).

1.4.2 LWT and growth rate effects on mammary development and milk production

1.4.2.1 LWT and growth rate pre-puberty

Rapid growth during the pre-pubertal allometric phase of mammary development mentioned previously, can give rise to excessive fat deposition in the mammary gland, termed "Fatty Udder Syndrome" (Moran 1996). However, there is conflicting evidence that rapid growth rates during this period will affect subsequent milk production, as illustrated in Table 1.14 below.

A feeding level that results in LWT gains above 600 – 700 g/d of heifers had a negative impact on the growth of mammary secretory tissue (Sejrsen 1994). However, this conclusion was based on studies where "feeding level" meant daily energy intake (Sejrsen 1994). Therefore, a high energy diet that caused a high LWT gain had a negative impact on the growth of secretory tissue in the mammary gland, not necessarily the quantity of feed provided. Furthermore, Chester-Jones et al. (2017) and Soberon et al. (2012) reported that pre-weaning and weaning LWT, and LWT gain post-weaning had positive effects on first-lactation and accumulated milk yields.

Table 1.14 First lactation milk production of heifers grown at various pre-pubertal growth rates fed diets differing in metabolizable energy (ME) and crude protein (CP).

Source	Age (mo)		LWT (kg)		ADG	Duration	1st lact	Diet
	Initial	Final	Initial	Final	(kg/d)	(mo)	Milk yield	ME:CP
Capuco et al. (1995) (USA HF, Feedlot)	7.7	-	175	325	0.786	3.4	21.7 (kg/d)	0.83
	7.7	-	175	325	0.788	4.0	20.7 (kg/d)	0.51
	7.7	-	175	325	0.992	3.5	19.6 (kg/d)	0.51
	7.7	-	175	325	1.001	3.0	20.6 (kg/d)	0.83
Macdonald et al. (2005) (NZ HF, pasture)	3.3	12.1	100	200	0.37	8.8	3243 (kg/yr)	0.5[1]
	3.3	9.9	100	200	0.53	6.6	3309 (kg/yr)	0.5
	3.3	7.7	100	200	0.77	4.4	3288 (kg/yr)	0.5
Macdonald et al. (2005) (NZ Jersey, pasture)	3.3	12.1	80	159	0.30	8.8	2535 (kg/yr)	0.5
	3.3	9.1	80	164	0.48	5.8	2629 (kg/yr)	0.5
	3.3	7.9	80	163	0.61	4.6	2579 (kg/yr)	0.5
Dobos et al. (2000) (Aus HF, feedlot)	5	10	114	-	0.918	5	18.8 (l/d)	0.77
	5	10	115	-	0.952	5	17.8 (l/d)	0.61
	5	10	122	-	0.990	5	19.4 (l/d)	0.60
Pirlo et al. (1997) (Ital. HF, feedlot)	3.1	14.5	89.6	300.9	0.608	11.4	22.7 (kg/d)	0.73*
	3.1	13.8	87.1	301.3	0.659	10.7	22.2 (kg/d)	0.60*
	3.1	12.1	85.7	301.9	0.794	9.0	20.2 (kg/d)	0.93*
	3.1	11.5	86.4	302.1	0.848	8.4	21.8 (kg/d)	0.70*
Moallem et al. (2010) (Israel HF, feedlot)	4.9	9.9	146.0	236.0	0.673	4.9	27.6[a] (kg/d)	0.80
	4.9	9.9	144.0	248.6	0.695	4.9	28.5[ab] (kg/d)	0.92
	4.9	9.9	147.7	256.2	0.730	4.9	29.1[b] (kg/d)	0.92
	4.9	9.9	146.0	263.2	0.742	4.9	31.0[c] (kg/d)	0.80

* Calculated as ME = 1.01 x (4.409 x TDN) – 0.45 (National Research Council 2001a).

[1] Assumed average ME:CP for New Zealand pastures

In Holstein-Friesian heifers reared on pasture to achieve different growth rates, a high growth rate of 0.77 kg/day for Friesians from weaning (100 kg) until 200 kg did not negatively affect milk production in the first three lactations (Macdonald et al. 2005). A high growth rate of 0.61 kg/day for Jerseys (80 kg – 160 kg) in the same study did not negatively affect milk production until the third lactation (Macdonald et al. 2005). However, when the milk yields were adjusted for LWT at 60 days in milk, in all three lactations for Jerseys and in the first lactation for Friesians, milk yield was negatively affected by high pre-pubertal growth rates (Macdonald et al. 2005). The heifers that grew slower pre-puberty produced more milk than those that grew faster pre-puberty, once adjusted to a common LWT. The authors suggested that the superior size at calving may have masked any negative effects of accelerated growth rates during the pre-pubertal period. Heifers that experience accelerated growth rates will be heavier than heifers that experience slower growth rates over the same period. Therefore, correcting for LWT when comparing accelerated and slow growth rates does not make sense, as a heavier LWT is a direct result of accelerated growth.

The length of time on the period one growth treatment differed for each group, for HF heifers the treatments were imposed from 100 kg at 100 days of age until they reached 200 kg (Macdonald et al. 2005). As the period one growth rate increased, the length of time on the treatment decreased, resulting in treatments lasting for 267, 200 and 135 days, respectively for L1, M1 and H1 treatments; for the H1 treatment this was approximately 120 days before heifers attained puberty (Macdonald et al. 2005).

The growth rate can be estimated between each milestone using LWT and age data reported by Macdonald et al. (2005). The mean LWTs of the HF heifers in the "period one" treatments have been summarised in Table 1.15 below. From the start of period one until puberty (255 days) can be calculated as 0.59 kg/day for H1 heifers; made up of a 0.90 kg/d growth for 82 days, 0.53 kg/d for 53 days and 0.41 kg/d growth for 120 days. Using those growth rates, the majority of pre-pubertal growth appears to be much lower than 0.7 kg/day, which could explain why there was not a negative effect on milk production for H1 heifers. Using the same calculations for L1 heifers from the start of period one until puberty (319 days), the ADG was 0.47 kg/d, not much different from H1 heifers. However, the pattern of ADG was different with 0.65 kg/d for 82 days, 0.25 kg/d for 185 days and 0.96 kg/d for 52 days.

Both the L1 and the H1 heifers had similar pre-pubertal growth rates, had periods of pre-pubertal growth that exceeded 0.9 kg/d and periods that were less than 0.45 kg/d.

These L1 and H1 heifers had similar annual first (3,243 vs 3,288 kg), second (3,817 vs 3,723 kg) and third (4,169 vs 4,015 kg) lactation milk production. Indicating that although the pattern of pre-pubertal growth was different between treatments, there is no evidence of fatty udder syndrome occurring in these heifers.

Table 1.15 Mean live weight (kg) and age (days; d) of Holstein-Friesian heifers from the start of period one (P1) until calving. Modified from Macdonald et al. (2005).

Milestone	Treatment		
	L1	M1	H1
StartP1 (100 d)	100	100	100
6 mths	154	163	174
EndP1	201 (367d)	202 (300d)	202 (235d)
Puberty	251 (419d)	251 (383d)	251 (355d)
15 mths	281	323	347
EndP2 (22 mths)	382	425	452
Calving	408	451	476

L1=0.37 kg/d, M1=0.53 kg/d, H1=0.77 kg/d from 100 kg to 200 kg

A USA study with heifers fed a corn (C) or alfalfa/lucerne (A) silage diet in a feedlot system to achieve high (H) or low (L) growth rates pre-puberty, reported that an increased energy consumption prior to puberty attainment inhibited the growth of secretory tissue in the mammary gland (Capuco et al. 1995). The corn diet contained a lower CP percentage and higher energy content; therefore, a higher ME:CP ratio of 0.83 compared with 0.53 of the lucerne diet (Capuco et al. 1995). It was reported that fat deposition in the mammary gland was greatest (1,963 g) in HC heifers (Capuco et al. 1995). Heifers fed on both high and low corn diets also had greater body fat at slaughter compared to those fed either of the lucerne diets (Capuco et al. 1995). Which demonstrates that a high ME:CP diet fed to achieve high growth rates (1 kg/d) was associated with increased fat deposition in the body, and in the mammary gland.

Capuco et al. (1995) also determined that mammary gland growth was not reduced in the heifers reared to achieve high growth rates (0.97 kg/d) on the lucerne diet (HA) compared with those fed to achieve low growth (0.77 kg/d) on the same lucerne diet (LA). The DNA content in the mammary parenchyma of heifers was not statistically different (105 mg) between LA and HA heifers (Table 1.16). For heifers in the HC, the parenchymal DNA was 961 mg less than that of heifers in the LC treatment, which is an indicator of impaired mammary development (Capuco et al. 1995). The contrasts reported by Capuco et al. (1995) were diet and growth within diet, it was not reported whether there was a statistical difference between the growth treatments irrespective of diet. Numerically, there were smaller differences in parenchymal DNA between heifers in LC and LA (121 mg) and between LC and HA (226 mg) treatments and larger differences between HC and LA (840 mg) and between HC and HA (735 mg) treatments (Capuco et al. 1995). This demonstrated that heifers fed a low ME:CP (0.51) diet pre-puberty to achieve high growth rates, did not have inhibited mammary gland development compared with heifers fed a high ME:CP (0.83) diet to achieve high growth rates. In this study by Capuco et al. (1995), reduced secretory tissue development observed in slaughtered heifers did not correlate to reduced first lactation milk production of contemporary heifers (Table 1.14). This further emphasises that inhibited mammary gland growth is related to energy consumption pre-puberty and not necessarily to the rate of growth itself.

Table 1.16 Parenchymal DNA content of Holstein-Friesian heifers fed a diet high in lucerne or corn silage to achieve a high or low growth rate pre-puberty. Modified from Capuco et al. (1995).

Trt	Age (mo)		LWT (kg)		ADG	Period	Diet	Parenchymal
	Initial	Final	Initial	Final	(kg/d)	(mo)	ME:CP	DNA (mg)
LA	7.4	14.2	175	335	766	6.8	0.51*	1896
HA	7.7	13.0	175	338	974	5.3	0.51*	1791
LC	7.5	13.8	175	329	792	6.3	0.83*	2017
HC	7.6	12.4	175	331	1011	4.8	0.83*	1056

* Calculated as ME = 1.01 x (4.409 x TDN) – 0.45 (National Research Council 2001a).
LA=fed lucerne for low growth, HA=fed lucerne for high growth, LC=fed corn for low growth, HC=fed corn for high growth.

Increasing the CP content of the diet pre-puberty may reduce the area of fat deposition in the mammary gland and decrease the ratio of fat to secretory tissue (Table 1.17). Heifers that gained more than 900 g/d on a low ME:CP diet had a smaller area of fat tissue and a lower ratio of fat to secretory tissue at 16 months of age, compared with heifers on a high ME:CP diet (Dobos et al. 2000). Inclusion of high proportions of rumen undegradable protein in pre-pubertal diets tended to increase milk protein yields during the first lactation by 0.08 kg/d, in addition to lower fat deposition in the mammary gland (Dobos et al. 2000). The results from Dobos et al. (2000) and Capuco et al. (1995) demonstrate that the make-up of the diet may be an important factor in determining if "Fatty Udder Syndrome" will occur in heifers fed to attain high growth rates pre-puberty. Addition of higher proportions of CP in the diet may reduce the incidence of increased fat deposition in the udder. Therefore, in pasture-based systems where the ratio of ME:CP rarely exceeds 0.6 (Section 1.1; Table 1.1 and Table 1.2), "fatty udder syndrome" is unlikely to occur and be a problem (Table 1.17).

Table 1.17 Incidence of impaired mammary gland (MG) development due to various pre-pubertal growth rates of heifers fed diets differing in metabolizable energy (ME) and crude protein (CP) content.

Source	Age (mo)		LWT (kg)		ADG (kg/d)	Period (mo)	Diet ME:CP	MG development
	Initial	Final	Initial	Final				
Radcliff et al. (1997) (USA HF, feedlot	3	11.6	127	336	0.77	8.6	10% grain: 90% haylage	More extra parenchymal fat in faster growing heifers, no effect on DNA or RNA
	3	12.5	128	379	0.85	9.5		
	3	10.2	126	396	1.19	7.2	75% grain: 25% haylage	
	3	10.2	124	411	1.27	7.2		
Albino et al. (2015) (Brazil HF, feedlot)	7.8	-	213	283	1	-	0.77	More fat deposits
	7.8	-	213	285	1	-	0.72	
	7.8	-	213	270	1	-	0.63	No change in fat deposits
	7.8	-	213	288	1	-	0.61	
	7.8	-	213	285	1	-	0.56	
Whitlock et al. (2002) (USA HF, feedlot)	3.5	8.9	134	320	1.13	5.4	0.87	Less parenchymal DNA
	3.5	8.9	135	326	1.17	5.4	0.74	More parenchymal DNA
	3.5	8.7	134	320	1.18	5.3	0.63	
Capuco et al. (1995) (USA HF, feedlot)	7.4	14.2	175	335	0.766	6.8	0.51*	No effect
	7.7	13.0	175	338	0.974	5.3	0.51*	
	7.5	13.8	175	329	0.792	6.3	0.83*	
	7.6	12.4	175	331	1.011	4.8	0.83*	Inhibited mammary growth
Dobos et al. (2000) (Aus HF, feedlot)	4.5	16.2	115	386	0.924	11.7	0.77	Greater fat tissue area
	5.5	16.5	126	352	0.972	11.0	0.61	Lesser fat tissue area
	5.3	15.5	128	356	0.944	10.2	0.60	

* Calculated as ME = 1.01 x DE – 0.45 (National Research Council 2001a).

1.4.2.2 LWT and growth rate post-puberty

Previous studies have reported positive relationships between precalving LWTs and first lactation milk production (Dobos et al. 2001; McNaughton & Lopdell 2013; van der Waaij et al. 1997; Van Eetvelde et al. 2017). van der Waaij et al. (1997) reported positive fat, protein and milk yield responses in New Zealand dairy heifers to an increase in LWT at nine, 15 or 21 months of age. Similarly, Van Eetvelde et al. (2017) reported that heifers that were heavier at conception and first calving produced more ECM during first lactation compared with lighter heifers. Dobos et al. (2001) reported that heifers that were older (34 months of age) and heavier (621 kg) at first calving had the greatest milk yields out of the nine treatments of age and LWT at first calving. Similarly, heifers that were the youngest (25 months of age) and lightest (468 kg) had the lowest milk production (Dobos et al. 2001).

Furthermore, Van Amburgh et al. (1998) reported a positive relationship between post-calving LWT and first lactation milk production which accounted for more variation in milk production compared with prepubertal LWT gain. Irrespective of prepubertal growth rate treatment, heifers that were heavier (within 24 hours) post-calving had superior milk yields to those that were lighter. In addition, McNaughton and Lopdell (2013) reported a similar effect of proportion of target LWT between 15 to 18 months of age on first and second lactation yields (4.6 and 4.8 L per kg LWT in first and second lactation, respectively). These studies provide evidence of the positive effects of increased post-pubertal LWT on milk production.

However, only the linear effect of LWT was tested in the analysis by Van Eetvelde et al. (2017), McNaughton and Lopdell (2013) and van der Waaij et al. (1997), the quadratic effect of LWT on milk production was not tested and hence the relationship between LWT and milk production was assumed to be the same for light and heavy heifers. Furthermore, the studies reported by McNaughton and Lopdell (2013) and van der Waaij et al. (1997) included heifers ranging from Jersey to Holstein-Friesian and various forms of crossbreeds, the statistical model for the effects of LWT and target LWT on milk production were corrected to a common breed in both studies, meaning that breed differences could not be reported.

It is widely reported that selection for high milk production in dairy cattle is associated with reduced fertility (Berry et al. 2003). As previously mentioned, cows that lost less LWT in early lactation were more likely to survive longer in the herd compared with cows that lost a large amount of LWT (Wall et al. 2007). In the same study, the relationship between early lactation LWT change and milk production was opposite to that of survival with higher producing cows being more likely to lose more LWT in first lactation compared with lower producing cows (Wall et al. 2007). The authors hypothesized that the lighter animals that were still growing in early lactation were partitioning energy towards growth and away from milk production with positive effects on overall survival, whereas, the heavier animals were partitioning more energy away from growth and towards milk production with negative effects on survival (Wall et al. 2007). In contrast, a high plane of nutrition during the second year (from one-year-old until three months of gestation) did not increase milk production during first lactation, but negatively affected reproduction compared with a low plane of nutrition (Lacasse et al. 1993).

Table 1.18 Incidence of impaired milk production due to growth rate post-puberty.

Source	Age (mo)		LWT (kg)		ADG	Duration	1st lact	Diet
	Initial	Final	Initial	Final	(kg/d)	(mo)	milk yield	ME:CP
Hoffman et al. (1996) (USA HF, feedlot)	10.0	25.6	315	664	0.763	15.6	25.4 (kg/d)	0.63*
	9.8	23.6	313	638	0.792	13.8	26.4 (kg/d)	
	9.8	22.7	318	663	0.897	12.9	24.6 (kg/d)	0.68*
	9.9	20.6	312	622	0.969	10.7	24.1 (kg/d)	
Macdonald et al. (2005) (NZ HF, pasture)	9.9	22	200	385	0.49	12.1	3,165[a] (kg/yr)	0.5[1]
	9.9	22	200	455	0.69	12.1	3,394[b] (kg/yr)	0.5[1]
Macdonald et al. (2005) (NZ Jersey, pasture)	9.7	22	165	320	0.43	12.3	2504[a] (kg/yr)	0.5[1]
	9.7	22	165	376	0.58	12.3	2658[b] (kg/yr)	0.5[1]

* Calculated as ME = 1.01 x (4.409 x TDN) – 0.45 (National Research Council 2001a).
[1] Assumed average ME:CP for New Zealand pastures

Results from a Norwegian study reported that there was a significant relationship between growth rate from 10 to 15 months of age and first lactation milk production of Norwegian Red heifers (Storli et al. 2017). However, the study by Storli et al. (2017) did not report differences in growth pattern between ages, provided the heifers ended up similar in LWT. As discussed in Section 1.2.1, growth rate over a set period is related to LWT and growth rate prior to and after the growth period studied. Therefore, it is important when analysing the effects of growth on a particular variable to disentangle whether it is the initial LWT, final LWT or AGR that is having the greatest effect.

There are few studies that have analysed milk production accumulated over multiple lactations, the majority of which included data only from surviving cows (Archer et al. 2013; Bettenay 1985; Heinrichs & Heinrichs 2011; Hutchison et al. 2017; Lin et al. 1988; Soberon et al. 2012). Of these studies there were only two that examined the relationship between LWT and accumulated milk production over multiple lactations (Bettenay 1985; Heinrichs & Heinrichs 2011), both of which concluded that there was no relationship between LWT and milk yield.

Bettenay (1985) had a small sample size of 18 heifers per treatment when comparing four ages and two LWTs at breeding. After breeding, heifers were run together, allowing the smaller heifers to grow faster and catch up to the larger heifers (Bettenay 1985). Additionally, only heifers that completed all four lactations were used to estimate accumulated yield over four lactations, heifers that completed fewer than four lactations were not included. Analysing the relationship including only the survivors does not truly describe the impact of light heifers on milk production, as it does not take into account how long the heifers actually remained productive for, in addition to the decreased milk production (Archer et al. 2013). The study by Heinrichs and Heinrichs (2011) included multiple fixed effects such as age at first calving and age at weaning, which might have been confounded with LWT at first calving. This may explain why they observed no relationship between LWT and lifetime milk yields.

1.5 Summary and Implications

There are recommended target LWTs for dairy heifers, however, these are based on a proportion of mature LWT which can only be estimated accurately once the heifer reaches maturity. Furthermore, the growth trajectory required to achieve the target LWTs is linear; however, the growth of New Zealand dairy heifers follows the seasonal variations in pasture quality and quantity. It is not known what the effect of LWT and growth rates has on future milk production, reproductive performance and longevity in New Zealand dairy heifers.

Therefore, the main objectives of the work presented in this thesis were:

- To model growth curves of New Zealand dairy heifers of F, J and FxJ crossbreed makeup to estimate their LWT and growth from three to 22 months of age.
- To use the estimated LWTs from three to 21 months of age to understand the relationships between precalving LWTs and milk production and precalving LWTs and reproduction and survival in New Zealand dairy heifers.
- To retrospectively and prospectively explore the relationships between growth pattern during rearing and subsequent milk production and reproductive performance.

Chapter 2 Live weight and growth of Holstein-Friesian, Jersey and crossbred dairy heifers in New Zealand

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2.1 Abstract

The objective of this study was to model growth of dairy heifers to estimate the effects of breed and heterosis on live weight (LWT) and growth from three to 22 months of age. Data comprised of 1,653,214 LWT records obtained from 189,936 dairy heifers in 1,547 herds. At all ages Holstein-Friesian (F) heifers were heavier than Holstein-Friesian-Jersey crossbred (FxJ) which were heavier than Jersey (J) heifers. Heterosis effects for LWT were greatest at nine months of age (3.6%) and least at 22 months of age (2.0%). The growth pattern differed, as evidenced by the regression coefficients of the Legendre polynomial. Growth was non-linear and heterosis effects were different throughout the growth period. Friesian, J and F×J heifers exhibited different growth patterns. These differences in growth pattern should be considered when formulating target LWTs and growth rates for a pasture-based system.

2.2 Introduction

The predominant dairy breed categories in New Zealand are Holstein-Friesian (F; 33.0%), Jersey (J; 9.3%) and Holstein-Friesian-Jersey crossbred (F×J; 48.0%) (Livestock Improvement Corporation & DairyNZ 2017). Holstein-Friesian is considered a later maturing and heavier breed than J (Burke et al. 1998; Leche 1971). Hickson et al. (2011) reported that J heifers attained puberty at a younger age than F heifers, further emphasising their earlier maturity. Positive heterosis for mature live weight (LWT) has been reported in F×J cattle and ranged from 7.2 kg to 10 kg (Harris 2005; Harris et al. 1996). It would be expected that growing F×J heifers would also exhibit heterosis for LWT, although there are no estimates in the literature.

The recommended target LWTs for dairy heifers are 30% of mature LWT at six months of age, 60% at 15 months (mating) and 90% at 22 months (pre-calving) (Troccon 1993; Wathes et al. 2014). However, differences in the proportion of target LWT achieved between breeds at different ages have been reported (Handcock et al. 2016; McNaughton & Lopdell 2013), indicating that the appropriate target percentage may be different among breeds.

In pastoral farming systems, dairy heifers tend to follow a seasonal pattern of growth that matches pasture quality and quantity (Handcock et al. 2016; Litherland et al. 2002), rather than the linear trajectory that the target LWTs infer. Thus, the growth trajectory of heifers is likely to be influenced by breed and heterosis, as well as a range of environmental factors including feed supply and nutrition. An understanding of the potential breed and heterosis effects is needed to refine growth targets for heifers of different breeds and crosses under a pastoral system.

The objective of this study was to model growth curves of dairy heifers to estimate the effects of breed and heterosis on the LWT and growth from three to 22 months of age.

2.3 Materials and methods

2.3.1 Dataset

Liveweight records of New Zealand dairy heifers were extracted from the Livestock Improvement Corporation database. Heifers that were born from June to December (spring-calving season) between the 2006-07 and 2013-14 dairy seasons were considered. The heifers had at least two LWT records between birth and 12 months of age and two LWT records between 13 months of age and first calving at two years of age (between June and December) or 24 months of age for heifers that did not have a recorded calving date at two years of age. Heifers that had a LWT record within 15 days of each age in months were included for that age. Only heifers with known dam and sire and ≤2/16 (12.5%) of breeds other than F or J were included in the initial dataset of 189,936 heifers with 1,657,856 LWT records. Of these heifers, 48,026 were F; 12,407 were J and 129,503 were F×J. Breeds were defined as follows: heifers that were at least 87.5% (14/16) F were classified as F; heifers that were at least 87.5% (14/16) J were classified as J; heifers that were neither F nor J were classified as F×J.

Based on recorded pedigree and sire and dam breed proportions; individual animals' breed proportions were known, and were used to calculate coefficient of specific heterosis between F and J, F and Other breeds (O), and J and O using the following formula:

$$h_{ij} = \alpha_{si}\alpha_{dj} + \alpha_{sj}\alpha_{di}$$

where h_{ij} is the coefficient of expected heterosis between breeds *i* and *j* in the progeny; α_{si} and α_{sj} are proportions of breeds *i* and *j* in the sire, respectively; and α_{di} and α_{dj} are proportions of breed *i* and *j* in the dam, respectively (Dickerson 1973).

Initial data cleaning was completed by calculating the mean and standard deviation of LWT for each month of age, and for each breed. Liveweight records that were more than four standard deviations from their corresponding breed-age mean were removed

(Pietersma et al. 2006). This method was iterated until no more records were deleted (Pietersma et al. 2006). This left a dataset comprised of 1,653,214 LWT records (1,423 removed) obtained from 189,936 dairy heifers located in 1,547 herds.

Heifers were born in the North (n=90,353) and South Island (n=99,583) of New Zealand. Age of dam was condensed into two ages: two years of age (n=13,717), and mixed-age (greater than two; n=176,219), where two-year-old dams were less than 30 months of age and mixed-age dams were greater than 30 months of age.

2.3.2 Growth curve model

Legendre polynomials of order two, three and four were fitted to LWT data using random regression to obtain an average growth curve for each heifer using ASReml (Gilmour et al. 2015). The goodness of fit achieved with the model was evaluated using the Akaike information criterion (AIC), coefficient of correlation (r), the coefficient of determination (r^2), the mean square prediction error (MSPE), mean prediction error (MPE) and relative prediction error (RPE) (O'Neill et al. 2013; Rook et al. 1990).

The MSPE was calculated as follows:

$$\text{MSPE} = (A_m - P_m)^2 + S_P^2(1-b)^2 + S_A^2(1-r^2)$$

Where A_m and P_m are the mean actual and predicted LWTs, respectively; S_A^2 and S_P^2 are the variances of the actual and predicted LWT, respectively; b is the slope of the regression of actual (A) on predicted (P) and r^2 is the coefficient of determination of A and P.

The three components of the MSPE are: mean bias $(A_m - P_m)^2$, line bias $S_P^2(1-b)^2$ and random variation $S_A^2(1-r^2)$. The proportion of MSPE that comes from random variation should be high if the model is predicting with good accuracy. If the proportion of random variation is low then there is a large proportion of the MSPE from the mean or line bias (O'Neill et al. 2013).

The MPE and RPE were calculated as follows:

$$\text{MPE} = \sqrt{\text{MSPE}}$$

$$\text{RPE}\ (\%) = \left(\frac{\text{MPE}}{A_m}\right) \times 100$$

The smaller the RPE, the more accurate the predictions are.

For all goodness of fit and accuracy measurements, the fourth-order Legendre polynomial predicted LWT the best (Table 2.1) and was selected as the most appropriate model to use.

To remove further outlier observations, the relative measurement error (RME) was calculated as:

$$\text{RME} = \frac{Predicted\ LWT - Actual\ LWT}{Predicted\ LWT} \times 100$$

The RME calculates the percentage deviation of the actual LWT from the predicted LWT by assuming that the predicted LWT is the "true" value. Ages where the model predicted LWT with an RPE greater than 6% were not considered when identifying outliers due to the predicted LWT not being accurate enough to be defined as the "true" value. For all other ages; any actual LWT that had an absolute RME greater than 18% (mean + four standard deviations) was considered an outlier and removed from the dataset. The new dataset (Order4-clean) was 1,653,214 observations (3,219 removed) on the same 189,936 animals. An order four Legendre polynomial was then fitted to "Order4-clean" and was used for subsequent analysis. The goodness of fit for this final model was evaluated as well as for each breed within the final model.

The estimates of the regression coefficients from the fourth order Legendre polynomial for each heifer were used to predict LWT at specific ages. The absolute growth rate (AGR) was calculated as (LWT_2 – LWT_1) / (t_2 – t_1). Where t_1 is the initial age in days, t_2 is the final age in days, and LWT_1 and LWT_2 are the corresponding predicted LWTs at these ages (Fitzhugh & Taylor 1971). The relative growth rate (RGR) was calculated as (ln (LWT_2) – ln (LWT_1)) / (t_2 – t_1) (Fitzhugh & Taylor 1971).

Table 2.1. Prediction accuracy of Legendre polynomials of order two, three and four for the prediction of live weight of New Zealand spring-born dairy heifers.

Model	N	r	r^2	MSPE $(kg)^2$	MPE (kg)	RPE (%)	AIC
Order2	1,656,433	0.993	0.987	168	12.95	5.37	11,996,927
Order3	1,656,433	0.995	0.990	132	11.48	4.76	12,020,779
Order4	1,656,433	0.997	0.994	81	9.00	3.73	11,769,901

r: coefficient of correlation, r^2: the coefficient of determination, MSPE: mean square prediction error, MPE: mean prediction error, RPE: relative prediction error, AIC: Akaike information criterion

2.3.3 Statistical analysis

The regression coefficients from the Legendre polynomial for each animal were analysed using linear mixed models that included the fixed effects of birth year, age of dam, island (North or South), the interaction between birth year and island, and the random effect of herd. Deviation from median birthdate (within-herd-year), proportion of F, proportion of O, heterosis F×J, heterosis F×O and heterosis J×O were fitted as covariates. The solutions of the mixed models were then used to predict the growth curves for heifers that were 16/16 F (F16), 16/16 J (J16), and first-cross F×J. The AGR and RGR curves for each breed were calculated from the growth curves.

Breed and heterosis effects for LWT and RGR at different ages were obtained using the same linear mixed model as above. Breed and heterosis effects for AGR at different ages were obtained using the same linear mixed model as for RGR with the addition of LWT at the initial age (LWT_1) fitted as a covariate. The estimates from the models were used to predict the LWT, AGR and RGR of F16, J16 and first-cross F×J heifers at different ages. Confidence intervals at the 95% level ($\mu \pm 1.96$ standard error) were used to test for differences among breeds.

2.4 Results

2.4.1 Comparison of Legendre Polynomials

The fourth order Legendre polynomial was selected as the preferred model as it predicted liveweight the best with the lowest RPE of 3.73%. At zero, one, two and 24 months of age the RPE was greater than 6% (21.74, 11.03, 6.49 and 6.28%, respectively). From three to 23 months of age the RPE was between 2.24 and 5.11%. Due to the consistent under prediction of LWT between zero and two months of age and at 24 months of age, and the small number of records at zero, one, 23 and 24 months of age (Appendix I), records were not removed during data cleaning at these ages due to the predicted LWT not being accurate enough to be defined as the "true" value. Consequently, growth curves have been evaluated from three to 22 months of age.

For the cleaned dataset of 1,653,214 LWTs on 189,936 heifers, the fourth-order polynomial predicted LWT with an RPE of 3.5% and an average bias between predicted and actual LWTs of 0.001 kg (Table 2.2). The MSPE was 72.8 kg^2 which predominantly came from random variation (0.997) with only a small proportion attributed to the line bias (0.003) and none to mean bias (0.000; Table 2.2).

The RPE for the different breeds ranged from 3.4 to 3.7% (Table 2.2). The bias between predicted and actual LWTs ranged from -0.607 to 1.340 kg (Table 2.2). The proportion of MSPE that came from random variation was high (0.964 – 0.998) and from the line bias and mean bias were low (0.002 – 0.008 and 0.000 – 0.030, respectively) for all breeds.

Table 2.2. Prediction accuracy of the fourth-order Legendre polynomial for the prediction of live weight (LWT) of Holstein-Friesian, Jersey and Holstein-Friesian-Jersey crossbred (FxJ) dairy heifers.

Category	Order4-clean	Breed		
		Holstein-Friesian	Jersey	FxJ
Number of records	1,653,214	399,716	99,785	1,153,713
Mean Actual LWT (A; kg)	241.25	257.75	209.89	238.24
Mean Predicted LWT (P; kg)	241.25	257.14	211.23	238.34
Regression of A upon P				
Intercept	-0.985	-1.145	-0.064	-0.848
Slope	1.004	1.007	0.994	1.003
r^2	0.994	0.994	0.994	0.994
Bias (P-A; kg)	0.001	-0.607	1.340	0.096
MSPE $(kg)^2$	72.8	78.4	59.0	72.0
Proportion of MSPE				
Mean bias	0.000	0.005	0.030	0.000
Line bias	0.003	0.008	0.006	0.002
Random variation	0.997	0.987	0.964	0.998
MPE (kg)	8.5	8.9	7.7	8.5
RPE (%)	3.5	3.4	3.7	3.6

r^2: the coefficient of determination, MSPE: mean square prediction error, MPE: mean prediction error, RPE: relative prediction error.

2.4.2 Growth curve model – shape and parameters

The growth curve as indicated by the regression coefficients differed among breeds for the intercept (α0), linear effect (α1), quadratic effect (α2), cubic effect (α3), and quartic effect (α4; Table 2.3).

Table 2.3. Estimates (± SEM) of the regression coefficients of the growth curve modelled with a fourth-order Legendre polynomial fitted to purebred Holstein-Friesian (F16), purebred Jersey (J16) and first-cross Holstein-Friesian-Jersey (F_1 F×J) heifers born between spring 2006 and spring 2013.

Breed	F16	F_1 F×J	J16
α0	356.20^a ± 0.68	343.39^b ± 0.68	312.64^c ± 0.71
α1	181.76^a ± 0.38	176.50^b ± 0.38	164.27^c ± 0.40
α2	-18.32^c ± 0.35	-14.78^b ± 0.35	-5.93^a ± 0.37
α3	-4.56^c ± 0.33	-0.78^b ± 0.33	3.65^a ± 0.34
α4	-28.70^c ± 0.28	-25.25^b ± 0.28	-20.42^a ± 0.29

F16=Holstein-Friesian, J16=Jersey, F_1 F×J= First cross Holstein-Friesian-Jersey
^{a,b,c}Values within row with different superscripts differ at the 95% confidence interval

2.4.3 Live weight

Live weight was different among breeds such that F16 heifers were heavier than F_1 F×J and J16 heifers throughout the growth period (Table 2.4, Figure 2.1). Estimates for breed and heterosis effects for liveweight are shown in Table 2.4. Breed differences between F16 and J16 were estimated to be greatest at 18 months of age. Heterosis, in absolute values was positive at all ages and greatest at 18 months of age. Heterosis (as a proportion of parent average) was greatest at nine months of age.

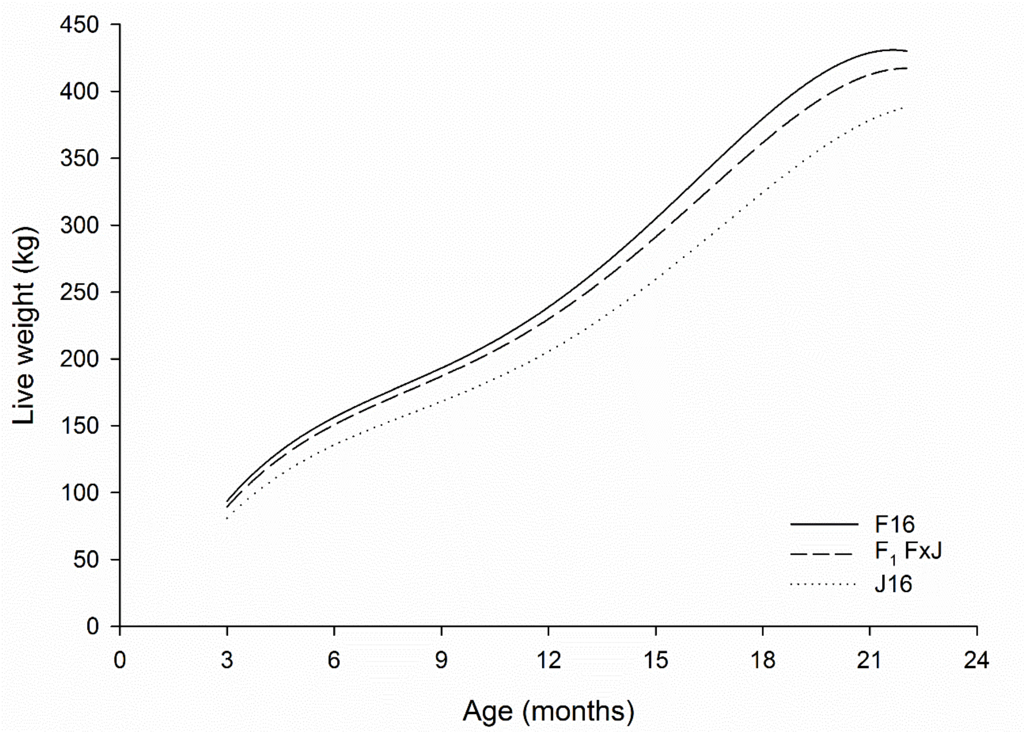

Figure 2.1 Predicted growth curves from three to 22 months of age for Holstein-Friesian (F16), Jersey (J16) and first-cross Holstein-Friesian-Jersey crossbred (F_1 F×J) dairy heifers born between spring-2006 and spring-2013.

2.4.4 Absolute growth rate

All breeds displayed seasonal variations in growth rate, as expected in a pasture-based system. Key periods of faster than average and slower than average growth can be identified from Figure 2.2. The periods of the fastest growth were between 3-5 months of age (spring to early-summer) and between 12-20 months of age (late-winter to summer). The first period of slower growth occurred between summer and winter of their first year (5-12 months of age). The second period of slowest growth occurred during the pre-calving period (20-22 months of age) when F16 heifers grew on average 0.205 kg/d, F_1 F×J and J16 heifers grew on average 0.239 and 0.263 kg/day, respectively (Table 2.4).

The mean AGR over the growth period studied (3-22 months) was greatest for F16 at 0.584 kg/day, intermediate for F_1 F×J and slowest for J16 (0.567 and 0.529 kg/day, respectively). The maximum average growth rate of 0.83 kg/d that was attained by F16 heifers occurred at 16 months of age, whereas the maximum average growth rate that J16 heifers attained was 0.72 kg/d which occurred approximately a month later (17 months; Figure 2.2). Heterosis for AGR was greatest between three and 12 months of age and was not significant between 20 and 22 months of age (Table 2.4).

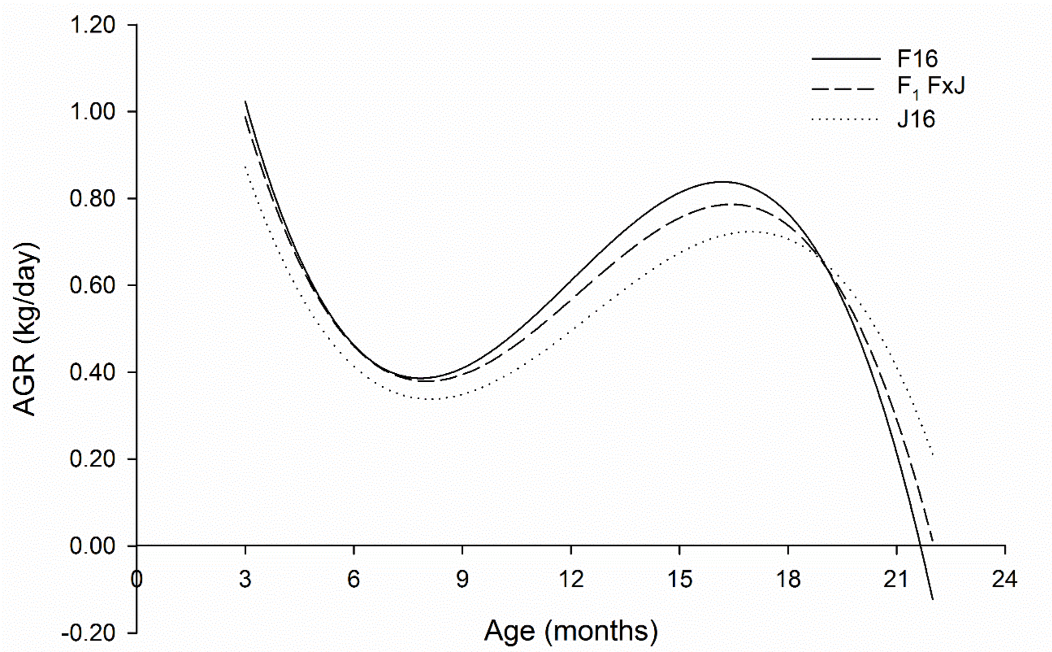

Figure 2.2 The absolute growth rate (AGR) from three to 22 months of age for Holstein-Friesian (F16), Jersey (J16) and first-cross Holstein-Friesian-Jersey crossbred (F_1 F×J) dairy heifers born between spring-2006 and spring-2013 estimated from a fourth-order Legendre polynomial.

2.4.5 Relative growth rate

The RGR followed a similar pattern for all breeds throughout the growth period studied (Figure 2.3). RGR was the greatest for all breeds at three months of age, followed by a rapid decline in RGR up to six months of age. Between six and 18 months of age, RGR was relatively stable between 0.2 and 0.3% per day, followed by a further decline up to 22 months of age.

Over the 3-22-month growth period studied, the RGR for J16 heifers were the fastest, followed by F_1 F×J, and F16 were the slowest (Table 2.4). This resulted in an overall small negative breed effect and a small negative heterosis effect (Table 2.4). As evidenced by the 95% CI, the RGR was similar for F16, F_1 F×J and J16 heifers from three to 12 months (Table 2.4). From 12-20 months of age, the RGR for J16 heifers was similar to F16, but greater for J16 heifers compared with F_1 F×J heifers (Table 2.4). By 20-22 months of age, J16 heifers were growing proportionally the fastest at 0.106% per day compared with F_1 F×J and F16 heifers which grew at 0.069% and 0.050% per day over this period.

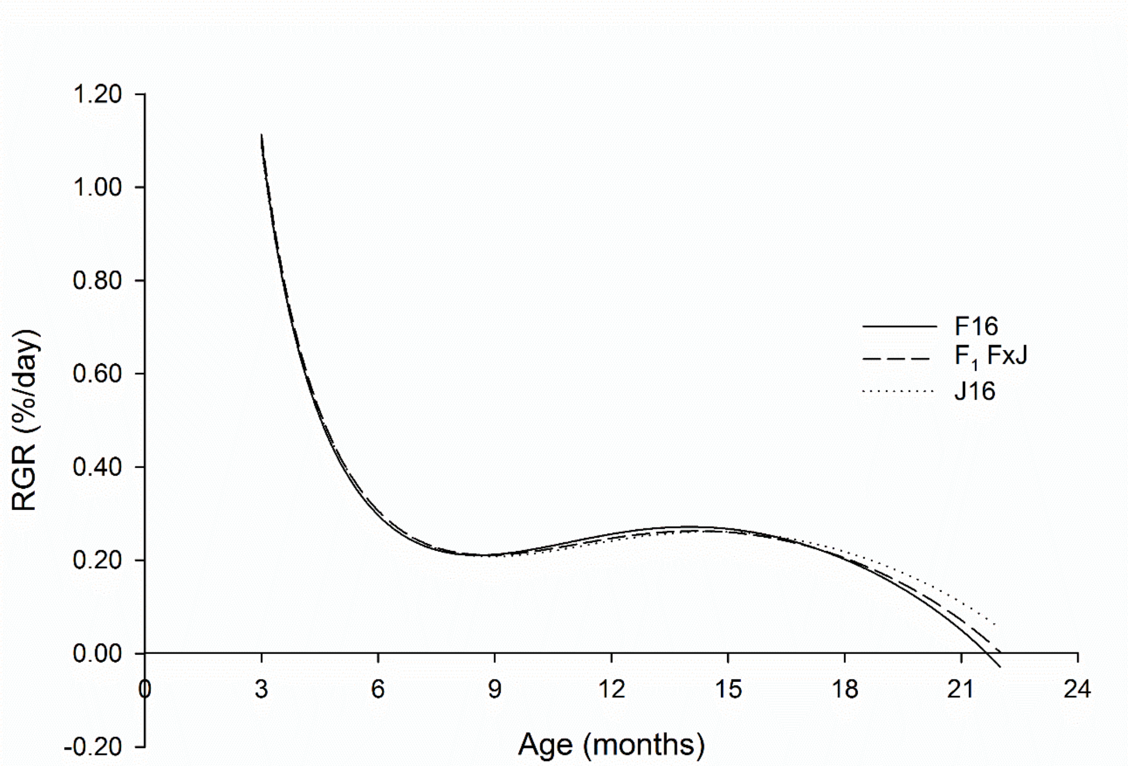

Figure 2.3 The relative growth rate (RGR) from three to 22 months of age for Holstein-Friesian (F16), Jersey (J16) and first-cross Holstein-Friesian-Jersey crossbred (F_1 F×J) dairy heifers born between spring-2006 and spring-2013 estimated from a fourth-order Legendre polynomial.

Table 2.4. Predicted live weight, absolute growth rate and relative growth rate (± SEM) of purebred Holstein-Friesian (F16), purebred Jersey (J16) and first-cross Holstein-Friesian-Jersey (F_1 F×J) heifers and estimates of breed and heterosis effects at different ages.

Age[1]	Breed			Breed effect	Heterosis (F×J)	
	F16	F_1 F×J	J16	F-J		%[2]
Live weight (kg)						
3	93.5[a] ± 0.3	89.2[b] ± 0.3	80.8[c] ± 0.3	12.8* ± 0.2	2.1* ± 0.1	2.4%
6	156.5[a] ± 0.5	150.9[b] ± 0.5	135.8[c] ± 0.5	20.7* ± 0.2	4.8* ± 0.2	3.3%
9	193.2[a] ± 0.6	187.1[b] ± 0.6	168.1[c] ± 0.6	25.1* ± 0.3	6.5* ± 0.2	3.6%
12	238.8[a] ± 0.7	230.0[b] ± 0.7	205.7[c] ± 0.7	33.1* ± 0.3	7.8* ± 0.3	3.5%
15	304.6[a] ± 0.7	291.1[b] ± 0.7	259.5[c] ± 0.8	45.2* ± 0.4	9.0* ± 0.3	3.2%
18	380.2[a] ± 0.8	362.2[b] ± 0.8	324.8[c] ± 0.8	55.3* ± 0.4	9.7* ± 0.3	2.8%
22	430.4[a] ± 0.7	417.4[b] ± 0.7	388.0[c] ± 0.8	42.4* ± 0.4	8.2* ± 0.3	2.0%
Absolute growth rate (kg per day)						
3-22	0.584[a] ± 0.001	0.567[b] ± 0.001	0.529[c] ± 0.001	0.055* ± 0.001	0.011* ± 0.001	2.0%
3-5	0.769[a] ± 0.004	0.755[a] ± 0.004	0.681[b] ± 0.005	0.088* ± 0.002	0.030* ± 0.002	4.2%
5-12	0.465[a] ± 0.003	0.444[b] ± 0.003	0.380[c] ± 0.003	0.085* ± 0.001	0.022* ± 0.001	5.1%
12-20	0.737[a] ± 0.003	0.694[b] ± 0.003	0.630[c] ± 0.003	0.107* ± 0.001	0.011* ± 0.001	1.6%
20-22	0.205[c] ± 0.006	0.239[b] ± 0.006	0.263[a] ± 0.006	-0.058* ± 0.003	0.004 ± 0.002	1.8%
Relative growth rate (% per day)						
3-22	0.266[c] ± 0.001	0.269[b] ± 0.001	0.274[a] ± 0.001	-0.008* ± 0.000	-0.001* ± 0.000	-0.4%
3-5	0.674 ± 0.003	0.685 ± 0.003	0.676 ± 0.004	-0.002 ± 0.002	0.010* ± 0.002	0.8%
5-12	0.250 ± 0.002	0.252 ± 0.002	0.252 ± 0.002	-0.002* ± 0.001	0.001 ± 0.001	0.1%
12-20	0.233[ab] ± 0.001	0.230[b] ± 0.001	0.235[a] ± 0.001	-0.002* ± 0.000	-0.004* ± 0.000	-0.8%
20-22	0.050[c] ± 0.001	0.069[b] ± 0.001	0.106[a] ± 0.002	-0.056* ± 0.001	-0.009* ± 0.001	-5.5%

*Mean is significantly different from zero ($P<0.001$).

[abc]Values within a row with different superscripts differ at the 95% confidence interval

[1]Age in months, where live weight for each age was predicted on the following days: 3 = 91 days, 5 = 152 days, 6 = 183 days, 9 = 274 days, 12 = 365 days, 15 = 456 days, 18 = 548 days, 20 = 608 days and 22 = 669 days.

[2]Expressed as a percentage of heterosis effects relative to the phenotypic average of the parental breeds ((F16+J16)/2).

2.5 Discussion

2.5.1 Goodness of fit

Fuentes-Pila et al. (1996) considered a model to be satisfactory when the RPE was less than 10%, therefore, the accuracy of the fourth-order Legendre polynomial for predicting LWT of dairy heifers in the current study was excellent (RPE less than 4%). Bryant et al. (2004) considered an RPE between 5% and 8% to be acceptable for predicting LWT of dairy heifers at puberty using a modified version of the von Bertanlaffy equation. For analysis, the results for MSPE that are presented in Table 2.2 are in terms of the proportional contribution of each of the three components to the MSPE. If the model is predicting LWT well, then the proportion of MSPE that comes from random variation will be high, as this is due to animal variation rather than a consistent bias from the model (O'Neill et al. 2013). The high random variation and low mean bias and line bias found in the current study suggests that the selected growth curve model is robust.

2.5.2 Growth curve

All breeds demonstrated seasonal variations in growth, with the periods of slowest growth occurring between 20 and 22 months of age. The average age at first calving for the heifers in the current study was 24 months of age, so the period of slow growth coincided with the period when heifers returned from a heifer rearing facility to the milking farm, were introduced to the herd and the nutrient requirements for foetal growth increased exponentially. Thomson et al. (1991) reported that the LWT gain of heifers in the three months prior to calving was 8 kg, compared with 33 kg for mature cows when heifers and mature cows were grazed together before heifers first calving. This may explain why the heifers in the current study showed minimal growth from 20 months onward.

In pasture-based systems, the majority of heifers rely entirely on pasture for their nutritional needs, whereas, in grain-based systems, diets are specifically formulated to meet nutritional needs (Waghorn & Clark 2004). Heifer performance on pasture is affected by both the quality and quantity of pasture on offer, both of which are determined by temperature and rainfall (Waghorn & Clark 2004). In periods of high pasture quality and/or quantity; for example, in spring, growth rates of heifers will be faster compared with periods of low pasture quality and/or quantity such as in midsummer (low rainfall) and mid-winter (low temperature). As seen in the present study, heifers grew slower in summer and winter than in spring.

The LWT of F16 heifers was consistently heavier than F_1 F×J and J16 heifers in the present study, as expected, based on the differences in mature size of 510 kg, 471 kg and 420 kg, respectively (Livestock Improvement Corporation & DairyNZ 2017). However, the growth pattern was different as demonstrated by different regression coefficients: the intercept (α0) and linear (α1) effects of the Legendre polynomial represent overall growth rate, so larger values denote faster overall growth. Quadratic (α2), cubic (α3) and quartic (α4) effects are related to the curvature of the growth curve. Greater absolute values for these three effects create more curvature in the pattern compared with values closer to zero. The intercept and linear effects were greater for F16 than for F_1 F×J and J16, which reflects that the overall growth rate was fastest for F16, intermediate for F_1 F×J, and slowest for J16. The mean regression coefficient for the cubic effect was negative for F16 and positive for J16 (Table 2.3). This difference in direction of the cubic effect reflects that F16 heifers did not gain weight between 21 and 22 months, whereas J16 continued to increase in LWT. This is also reiterated in that the breed effects for AGR were positive up to 20 months of age and negative between 20 and 22 months of age.

Heterosis estimates for mature F×J cows ranged from 7.2 kg to 10 kg (Harris 2005; Harris et al. 1996); similar to the values in the current study from nine months of age onwards. Heterosis varied throughout the growth period in first generation F×J heifers in the USA (Hilder & Fohrman 1949). Furthermore, heterosis for LWT exhibited by F_1 F×J heifers in the current study was the greatest (3.6%) at nine months of age and heterosis for AGR was greatest between three and 12 months of age. In beef heifers, the greatest effects of heterosis on growth rate were expressed from 200 to 400 days of age (approximately six – 13 months of age) (Gregory et al. 1978), similar to what was found in the present study. The difference in growth pattern among the breeds indicates that at different ages, one parent breed has a greater potential for growth compared with the other, and heterosis significantly contributes to the difference in growth pattern.

Animals that have heavy mature weights are generally later maturing compared with animals that have lighter mature weights (Taylor 1965). Similarly, animals that were heavier at maturity tended to be less mature at the same age compared with animals that were lighter at maturity (Fitzhugh & Taylor 1971). It would be expected that F16 heifers would be later maturing compared with J16 heifers, as F16 heifers were heavier than J16 heifers throughout the growth period studied, and mature F cows were heavier than mature J cows (Livestock Improvement Corporation & DairyNZ 2017). However, the RGR of F16 and J16 heifers in the present study were similar up to 20 months of age, which indicates that the breeds were maturing at similar rates, due to RGR being equal to the relative maturing rate, as demonstrated by Fitzhugh and Taylor (1971). Additionally, Butler-Hogg and Wood (1982) reported that at each age interval studied British F and J steers deposited similar proportions of body fat, which suggested that they were equally mature. Over the entire three to 22 months of age period studied the RGR of J16 was greater than F16 and F_1 F×J, suggesting J16 were in fact earlier maturing. However, this difference appears to be driven by growth near the end of the measurement period; just prior to first calving. The differences over this period were more likely to be due to the combination of foetal growth and body growth, rather than body growth alone. In addition, Jersey and F×J heifers were better able to reach target LWTs in the pasture-based system, compared with F heifers (McNaughton & Lopdell 2013). It was hypothesised that if heifers were in grazing mobs of mixed breeds then the feeding level provided may not have been sufficient for the larger F heifers (McNaughton & Lopdell 2013).

Common growth models for animals require an asymptote of mature LWT (e.g. Brody, von Bertalanffy, and Gompertz), however, this is not required for random regression. The LWT records on the heifers in the current study are only up until first calving, hence the heifers are still in the ascending growth stage with no information on mature LWT. If LWT measurements were available throughout the lifetime of the heifers in the current study, then a more traditional growth model would be appropriate and would enable further understanding on maturing rate differences among breeds.

The results from this study reiterate that heifer growth in a seasonal pasture-based system does not follow the linear trajectory that the target LWTs necessitate. Further research should be directed at understanding whether there are optimum growth trajectories for each breed in the pasture-based system to yield maximum milk production and reproductive performance.

2.6 Conclusions

Results reported here indicate that random regression using Legendre polynomials can accurately predict LWT and growth curves of dairy heifers. The results also showed that F, J and F×J cattle exhibit different absolute growth curves, and the expression of breed and heterosis effects varied throughout the growth period studied. Heifer growth in a seasonal pasture-based system does not follow the linear trajectory that the target LWTs dictate. Different growth patterns for each breed should be considered when formulating target LWTs and growth rates.

Foreword to Chapter 3

The previous chapter (Chapter 2), demonstrated that there were significant breed and heterosis effects on LWT and growth. Breed and LWT are confounded; for example, heavier heifers were more likely to have more Holstein-Friesian breed proportions than were lighter heifers. Therefore, breed and LWT cannot be included as fixed effects in the same model, as breed corrected for LWT or LWT corrected for breed does not give an estimate of the effect of LWT on milk production. Based on that, heifers were grouped into five breed groups ranging from more to less Friesian (Holstein-Friesian; F, Holstein-Friesian crossbred; FX, Holstein-Friesian-Jersey crossbred; FJ, Jersey crossbred; JX and Jersey; J) and the effect of LWT on milk production was modelled within each of the five breed groups to avoid the confounding of LWT and breed. Therefore, for each age studied, the effect of being heavier within each breed group was estimated, giving five estimates of the effect of LWT on milk production for each age group studied. This methodology was continued for Chapters 4, 5 and 6.

Chapter 3 Positive relationships between live weight of dairy heifers and their first lactation and accumulated three-parity lactation production

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Handcock RC, Lopez-Villalobos N, McNaughton LR, Back PJ, Edwards GR, Hickson RE. 2018. Dairy heifers: there is no such thing as too big. Proceedings of the Society of Dairy Cattle Veterinarians New Zealand Veterinary Association. 155-160.

Handcock RC, Lopez-Villalobos N, McNaughton LR, Back PJ, Edwards GR, Hickson RE 2019. Positive relationships between body weight of dairy heifers and their first-lactation and accumulated three-parity lactation production. Journal of Dairy Science 102: 4577-4589. http://dx.doi.org/10.3168/jds.2018-15229

3.1 Abstract

This study investigated the relationships between live weight (LWT) and milk production of 140,113 New Zealand dairy heifers. Heifers were classified into five breed groups; Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Jersey (J), Jersey crossbred (JX) and Holstein-Friesian-Jersey crossbred (FJ). Live weights were assessed at three-monthly intervals from three to 21 months of age and their relationships with first lactation and accumulated milk production over the first three lactations (three-parity) were analysed. There were positive curvilinear relationships between LWT and milk production. The response to an increase in LWT was greater for lighter heifers compared with heavier heifers, indicating there could be benefits of preferentially feeding lighter heifers to attain heavier LWTs. Within the age range and LWT range studied an increase in LWT was always associated with an increase in first lactation energy-corrected milk (ECM) and milksolids (milk fat plus milk protein) yield for breed groups other than F. For F heifers, there was a positive relationship between LWT and ECM and milksolids yields for all ages except for three months of age when no relationship existed. These results show the potential to increase first-lactation milk production of New Zealand dairy heifers by increasing heifer LWTs. Likewise, for three-parity accumulated yields, the LWTs at which maximum ECM and milksolids yields occurred were at the heavier end of the LWT range studied. The costs of rearing a heifer are incurred regardless of how long she remains in the herd. There is a potential bias from considering only cows that survived to lactate each year if particular cows had better survival than others. Therefore, the data in the current study for three-parity production includes all heifers that were old enough to have completed three lactations, regardless of whether they did or not. Including the heifers that did not complete all three lactations describes the effect that LWT of replacement heifers has on accumulated milk yields without discriminating whether the increased milk yield came from greater survival or from greater production per surviving cow. Further research on the relationships between LWT and survival of heifers is required to confirm whether the heavier heifers survived longer than the lighter heifers but could explain why the relationship between LWT and three-parity milk yields was more curvilinear than the relationship between LWT and first lactation milk production. Holstein-Friesian heifers that were 450 kg in LWT at 21 months of age were estimated to produce 168 and 509 kg more ECM than 425 kg F heifers in first-lactation and three-parity accumulated yields, respectively. A further increase in LWT at 21 months of age from

450 kg to 475 kg was estimated to result in 157 and 409 kg more ECM in first-lactation and three-parity accumulated yields, respectively. Consequently, for heifers that were average and below average in LWT, there would be considerable milk production benefits over the first three lactations by improving rearing practices to result in heavier heifers throughout the precalving phase.

3.2 Introduction

Replacement dairy heifers are required to calve at 24 months of age to initiate a 365-day calving interval required in a seasonal pasture-based dairy farming system. In year-round calving systems an age at first calving between 22 and 24 months of age is recommended for optimal economic returns (Ettema & Santos 2004; Hutchison et al. 2017). In order to calve at 24 months of age, heifers need to have attained puberty by, and get pregnant at 15 months of age. Puberty in heifers occurs between approximately 45 to 55% of mature live weight (LWT) (Freetly et al. 2011; McNaughton et al. 2002). To ensure that heifers have attained puberty before breeding, the industry recommended target LWT at breeding is 60% of mature LWT (Troccon 1993; Wathes et al. 2014). More beef heifers that were bred to their third oestrus were pregnant (78%) compared with heifers that were bred to their first oestrus (57%), suggesting that fertility improves over the first few oestrous cycles (Byerley et al. 1987). Therefore, it is advantageous to have all heifers pubertal before breeding.

Generally, in a seasonal pasture-based dairy farming system all of the cows in the herd are dried off around the same time, therefore, cows that calved earlier in the calving period will have had a longer lactation compared with cows that calved later, enabling more productive days and hence greater milk yields (Macdonald et al. 2008). A greater proportion of heifers that calved early as two-year-olds (within 21 days of herd planned start of calving; PSC) also calved early (within 42 days of herd PSC) as three-year-olds compared with heifers that calved later (after 21 days from herd PSC) (Pryce et al. 2007). This relationship between earliness of calving in subsequent years emphasises the importance of early calving heifers, as they are likely to become early calving cows. More heifers that were heavier at breeding were pubertal and calved earlier than heifers that were lighter at breeding (Archbold et al. 2012). In addition, more of the heavier heifers were present at the beginning of first (93% vs 82%) and second (76% vs 62%) lactation compared with the lighter heifers (Archbold et al. 2012). Further emphasizing the reproductive and longevity benefits of having heavier heifers at breeding.

Positive linear relationships between precalving LWT and first lactation milk production, and percentage of target LWT and milk production have been reported in New Zealand (McNaughton & Lopdell 2013; van der Waaij et al. 1997). These studies estimated 5 to 6 L of milk was produced in first lactation for each extra kg of LWT between nine and 22 months of age. McNaughton and Lopdell (2013) also reported a similar effect of LWT between 15 to 18 months of age on second lactation yields (4.8 L per kg LWT). These results indicate that greater milk production can be achieved in first and second lactations by growing heifers to greater LWT but a curvilinear relationship was not considered in these studies.

The major dairy breeds in New Zealand are Holstein-Friesian (33.0%), Jersey (9.3%) and Holstein-Friesian-Jersey crossbred (FxJ; 48.0%); with a large range of Holstein-Friesian and Jersey breed proportions within the FxJ breed. Jersey heifers produced less milk (Livestock Improvement Corporation & DairyNZ 2017; Sneddon et al. 2016a) and were lighter (Chapter 2) than FxJ and Holstein-Friesian heifers. The aforementioned milk production studies (McNaughton & Lopdell 2013; van der Waaij et al. 1997) did not compare the relationships between LWT and milk production among heifers of differing breed makeup.

The recommended target LWTs for dairy heifers in New Zealand and elsewhere are based on percentages of mature LWT (National Research Council 2001b; Troccon 1993; Wathes et al. 2014). The target growth trajectory between the target LWTs is predominantly linear. However, heifer growth in a seasonal pasture-based system did not follow the linear trajectory that the target LWTs necessitated (Chapter 2). Furthermore, the growth pattern of Holstein-Friesian, Jersey and FxJ heifers differed throughout the rearing phase (Chapter 2), suggesting there may be breed-specific optimum LWTs to yield maximum milk production.

The aim of the current study was to explore the relationships between precalving LWTs and milk production in New Zealand dairy heifers of varying breed makeup over multiple lactations.

3.3 Materials and methods

3.3.1 Initial dataset

The initial dataset was extracted from the Livestock Improvement Corporation national dairy database and consisted of 189,936 spring-born heifers born between 2006-07 and 2013-14 spring-calving dairy seasons and located in 1,547 herds throughout New Zealand. Heifers were included if they had at least two LWT records between birth and 12 months of age and at least two LWT records between 13 months of age and first calving at 2 years of age (between June and December) or 24 months of age for heifers that did not have a recorded calving date at 2 years of age. Growth curves were generated for each heifer using random regression of a fourth-order Legendre polynomial in ASReml (Gilmour et al. 2015) as described in (Chapter 2). Using the regression coefficients from the growth curves, LWTs were predicted for each heifer at three, six, nine, 12, 15, 18 and 21 months of age in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

Breed composition (expressed in 16th) based on pedigree information was used to classify heifers into one of 5 breed groups; Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Jersey (J), Jersey crossbred (JX) or Holstein-Friesian-Jersey crossbred (FJ). The criteria used to classify breed groups is outlined in Table 3.1. All heifers in the dataset were 16/16 pedigree recorded and were no more than 2/16 of any breed other than Holstein-Friesian or Jersey.

3.3.2 First-lactation dataset

Additional data of calving dates and milk production records were extracted from the Livestock Improvement Corporation database and merged with the growth curves of the 189,936 heifers. Heifers were selected that calved at approximately 2 years of age (21 – 29 months of age) in the spring-calving period (between June and December; n=175,142).

Heifers with a first lactation length of less than 80 days were excluded, additionally, records outside of the following limits were also excluded: 30 – 300 kg of milk protein, 40 – 400 kg of milk fat, 800 – 8000 L of milk yield. Lactations that were greater than 305 days were truncated at 305 days. This resulted in 140,113 heifers with suitable first-lactation records located in 1,326 herds (Table 3.1).

3.3.3 Three-parity production dataset

A dataset was created to examine the impact of LWT on milk production accumulated over the first three lactations (three-parity production); provided the heifer was old enough to complete three lactations. The starting dataset was the "First-lactation" dataset and was merged with second and third calving dates and milk production records that were extracted from the Livestock Improvement Corporation database (2008/09 to 2016/17 spring-calving dairy seasons).

Heifers born after the 2012/13 spring-calving dairy season (n=50,584) were removed from the dataset as at the time of data extraction they were not old enough to have had 3 full lactations. The remaining 89,529 heifers were subject to the following criteria: heifers with a calving date but no milk yields (n=12,445) were removed from the dataset due to not knowing whether they were not herd tested or if they did not lactate. Second and third lactation yields were subject to the same criteria as first lactation yields: 30 – 300 kg of milk protein, 40 – 400 kg of milk fat, 800 – 8000 L of milk yield, and lactation length of greater than 80 days. Any heifer with a record outside of those limits (n=9,251) was excluded from the analysis. Lactations that were greater than 305 days were truncated at 305 days to remove any heifers that were milked for extended lactations that were atypical of the New Zealand system.

Three-parity production was calculated as the sum of up to the first three lactations milk, fat or protein yields. Three-parity production was equivalent to first-parity production for heifers that did not have a recorded second calving date. Likewise, three-parity production was equivalent to the sum of first- and second-parity production for heifers that did not have a recorded third calving date. After these data edits there were 67,833 heifers remaining in the dataset that during first lactation were located in one of 910 herds (Table 3.1).

Table 3.1 Breed composition and number of records (N) for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) and Jersey (J) heifers included in the live weight (LWT), first lactation (First) and accumulated three-parity production (3-parity) datasets.

Breed group	Breed composition	N (LWT)	N (First)	N (3-parity)[1]
F	F ≥ 14/16	47,852	34,936	16,382
FX	10/16 ≤ F ≤ 13/16	62,310	46,690	22,192
FJ	F < 10/16 and J < 10/16	42,842	31,373	15,154
JX	10/16 ≤ J ≤ 13/16	24,184	17,395	8,672
J	J ≥ 14/16	12,352	9,719	5,433
Total	-	189,936	140,113	67,833

[1]Only heifers born between spring 2006/07 and spring 2012/13 were included for three-parity analysis

3.3.4 Data handling

The energy-corrected milk (ECM) yield formula used was from Beever and Doyle (2007), and derived from Tyrell and Reid (1965) and calculated as follows:

ECM = milk yield × (383 × fat percentage + 242 × protein percentage + 783.2)/3,140

Milksolids were calculated as the sum of milk fat and milk protein yields (lactose not included).

3.3.5 Statistical analysis

Least squares means for each breed group for first lactation and three-parity milk parameters were obtained using mixed models in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The models included the fixed effects of breed group (F, FX, FJ, JX, J), the covariate deviation from median date of first calving (within herd-year), and the random effect of herd-year. Herd-year was defined as the herd and year in which the heifer was located during first lactation.

Live weights were considered at three, six, nine, 12, 15, 18 and 21 months of age. The effects of LWT on milk production parameters in first lactation and three-parity production were analysed using mixed models; LWT at each age were fitted separately. The models included the fixed effects of breed group (F, FX, FJ, JX, J), the linear and quadratic effects of LWT within breed group, the covariate deviation from median date of first calving (within herd-year), and the random effect of herd-year.

For each breed group-age combination, LWT at which maximum milk production was observed was determined by calculating the LWT at which the first derivative with respect to LWT of the solution from the mixed model was zero, for models in which the quadratic effect of LWT was significant ($P<0.05$).

3.4 Results

3.4.1 Breed group milk production

Jersey heifers produced the least ($P<0.01$) ECM and milksolids in first and three-parity lactations (Table 3.2). First lactation yields of ECM were greater ($P<0.01$) for FX heifers compared with F heifers. Holstein-Friesian and FJ heifers had similar ($P>0.05$) ECM yields in first lactation but accumulated three-parity ECM yields were lesser ($P<0.01$) for F than FX and FJ heifers.

Milksolids production of FX and FJ heifers were similar ($P>0.05$) in first and three-parity lactations (Table 3.2). Furthermore, three-parity milksolids production was not different ($P>0.05$) for F and JX heifers, both produced less ($P<0.01$) than FX and FJ heifers but more ($P<0.01$) than J heifers (Table 3.2).

Table 3.2 Number of records (N) and least squares means ± sem of energy-corrected milk (ECM) and milksolids (MS) in first lactation and accumulated three-parity production for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) and Jersey (J) cows.

	N	ECM (kg)	MS (kg)
First lactation			
F	34,936	$3,970.8^{b}$ ± 19.9	301.6^{b} ± 1.5
FX	46,690	$3,997.3^{a}$ ± 19.7	305.6^{a} ± 1.5
FJ	31,373	$3,971.7^{b}$ ± 19.9	305.0^{a} ± 1.5
JX	17,395	$3,894.0^{c}$ ± 20.2	300.0^{c} ± 1.5
J	9,719	$3,694.5^{d}$ ± 23.1	286.1^{d} ± 1.8
Three-parity[1]			
F	16,382	$10,311.0^{b}$ ± 102.5	782.5^{b} ± 7.9
FX	22,192	$10,635.0^{a}$ ± 99.7	813.1^{a} ± 7.7
FJ	15,154	$10,624.0^{a}$ ± 102.3	816.9^{a} ± 7.9
JX	8,672	$10,264.0^{b}$ ± 107.1	792.3^{b} ± 8.2
J	5,433	$9,466.0^{c}$ ± 140.4	735.0^{c} ± 10.8

$^{a-d}$Values within column and parameter with different superscripts differ between breed groups ($P<0.01$)

[1]Only heifers born between spring 2006/07 and spring 2012/13 were included for three-parity analysis

3.4.2 First lactation

Live weight at three to 21 months of age had significant linear and quadratic effects on first lactation milk yields (Table 3.3 & 0). Heifers of all breed groups that were heavier at six, nine, 12, 15, 18 and 21 months of age produced more ECM and milksolids compared with heifers that were lighter (P<0.05; Table 3.3 & 0). For F heifers, there was a positive relationship between LWT and milk production for all ages except for 3 months of age when no relationship existed (P>0.05; Table 3.3 & 0). The linear effects of LWT were positive, the quadratic effects of LWT were negative and were more likely to be significant at older ages (15, 18 and 21 months of age) compared with younger ages (less than 15 months of age; Table 3.3 & 0).

Table 3.3 Intercept and regression coefficients ± s.e. for the linear and quadratic effects of live weight (LWT) from three to 21 months of age of dairy heifers on energy-corrected milk (ECM) yield in first lactation.

Breed group[1]	Intercept (kg ECM)	P value[2]	Linear (kg ECM/kg LWT)	P value	Quadratic (kg ECM/kg LWT^2)	P value
			3 months of age			
F	3380.1 ± 128.1	<0.001	4.32 ± 2.65	0.102	0.0242 ± 0.0137	0.078
FX	3045.2 ± 108.5	<0.001	11.45 ± 2.33	<0.001	-0.0075 ± 0.0126	0.552
FJ	3132.2 ± 123.7	<0.001	10.05 ± 2.75	<0.001	-0.0030 ± 0.0154	0.844
JX	3103.2 ± 155.8	<0.001	10.41 ± 3.58	0.004	-0.0101 ± 0.0206	0.624
J	2370.8 ± 218.9	<0.001	23.37 ± 5.22	<0.001	-0.0803 ± 0.0311	0.010
			6 months of age			
F	2445.0 ± 153.9	<0.001	10.49 ± 1.90	<0.001	-0.0032 ± 0.0058	0.588
FX	2361.2 ± 131.8	<0.001	11.75 ± 1.67	<0.001	-0.0057 ± 0.0053	0.281
FJ	2161.4 ± 159.1	<0.001	14.75 ± 2.09	<0.001	-0.0163 ± 0.0069	0.018
JX	2339.5 ± 201.1	<0.001	12.25 ± 2.73	<0.001	-0.0094 ± 0.0092	0.309
J	2224.3 ± 286.1	<0.001	12.12 ± 4.11	0.003	-0.0087 ± 0.0147	0.553
			9 months of age			
F	1957.1 ± 176.5	<0.001	11.22 ± 1.73	<0.001	-0.0042 ± 0.0042	0.326
FX	2045.2 ± 150.6	<0.001	10.66 ± 1.52	<0.001	-0.0023 ± 0.0038	0.553
FJ	1638.3 ± 188.3	<0.001	15.09 ± 1.96	<0.001	-0.0138 ± 0.0051	0.007
JX	2050.1 ± 249.8	<0.001	10.84 ± 2.69	<0.001	-0.0038 ± 0.0072	0.596
J	1745.5 ± 388.4	<0.001	12.73 ± 4.42	0.004	-0.0080 ± 0.0125	0.522
			12 months of age			
F	1591.4 ± 200	<0.001	10.94 ± 1.56	<0.001	-0.0048 ± 0.0031	0.121
FX	1830.9 ± 172.1	<0.001	9.28 ± 1.39	<0.001	-0.0010 ± 0.0028	0.728
FJ	1295.7 ± 214.8	<0.001	13.81 ± 1.80	<0.001	-0.0101 ± 0.0037	0.007
JX	1499.2 ± 284.0	<0.001	12.43 ± 2.46	<0.001	-0.0083 ± 0.0053	0.119
J	910.8 ± 438.6	0.038	16.74 ± 4.04	<0.001	-0.0174 ± 0.0092	0.061
			15 months of age			
F	770.8 ± 249.1	0.002	12.88 ± 1.53	<0.001	-0.0083 ± 0.0023	<0.001
FX	997.8 ± 218.1	<0.001	11.79 ± 1.39	<0.001	-0.0064 ± 0.0022	0.004
FJ	588.7 ± 271.7	0.030	14.56 ± 1.79	<0.001	-0.0106 ± 0.0030	<0.001
JX	445.8 ± 350.4	0.203	16.14 ± 2.40	<0.001	-0.0144 ± 0.0041	<0.001
J	57.9 ± 522.8	0.912	18.22 ± 3.85	<0.001	-0.0175 ± 0.0071	0.013
			18 months of age			
F	329.1 ± 303.1	0.278	12.27 ± 1.50	<0.001	-0.0073 ± 0.0019	<0.001
FX	-81.1 ± 267.1	0.761	14.77 ± 1.38	<0.001	-0.0104 ± 0.0018	<0.001
FJ	88.5 ± 333.2	0.791	14.08 ± 1.78	<0.001	-0.0095 ± 0.0024	<0.001
JX	-163.5 ± 415.3	0.694	16.15 ± 2.31	<0.001	-0.0133 ± 0.0032	<0.001
J	-655.6 ± 588.0	0.265	18.56 ± 3.52	<0.001	-0.0165 ± 0.0053	0.002
			21 months of age			
F	-648.7 ± 373.7	0.083	14.63 ± 1.66	<0.001	-0.0091 ± 0.0019	<0.001
FX	-1157.1 ± 331.2	0.001	17.34 ± 1.52	<0.001	-0.0121 ± 0.0018	<0.001
FJ	-967.7 ± 410.5	0.018	16.83 ± 1.95	<0.001	-0.0118 ± 0.0023	<0.001
JX	-431.4 ± 506.7	0.395	14.91 ± 2.49	<0.001	-0.0103 ± 0.0031	<0.001
J	-2229.8 ± 762.5	0.004	23.87 ± 4.01	<0.001	-0.0218 ± 0.0053	<0.001

[1]Where F is Holstein-Friesian, FX is Holstein-Friesian crossbred, FJ is Holstein-Friesian-Jersey crossbred, JX is Jersey crossbred and J is Jersey.
[2]P value tests that the corresponding regression coefficient is significantly different from zero.

Table 3.4 Intercept and regression coefficients ± s.e. for the linear and quadratic effects of live weight (LWT) from three to 21 months of age of dairy heifers on milksolids[1] (MS) yield in first lactation.

Breed group[2]	Intercept (kg MS)	P value[3]	Linear (kg MS/kg LWT)	P value	Quadratic (kg MS/kg LWT^2)	P value
			3 months of age			
F	259.4 ± 9.8	<0.001	0.31 ± 0.20	0.126	0.0017 ± 0.0011	0.100
FX	236.2 ± 8.3	<0.001	0.84 ± 0.18	<0.001	-0.0006 ± 0.0010	0.552
FJ	241.8 ± 9.5	<0.001	0.77 ± 0.21	<0.001	-0.0004 ± 0.0012	0.735
JX	240.9 ± 12.0	<0.001	0.80 ± 0.28	0.004	-0.0010 ± 0.0016	0.544
J	183.2 ± 16.8	<0.001	1.84 ± 0.40	<0.001	-0.0065 ± 0.0024	0.007
			6 months of age			
F	190.3 ± 11.8	<0.001	0.76 ± 0.15	<0.001	-0.0002 ± 0.0004	0.709
FX	183.4 ± 10.1	<0.001	0.87 ± 0.13	<0.001	-0.0004 ± 0.0004	0.334
FJ	163.8 ± 12.2	<0.001	1.17 ± 0.16	<0.001	-0.0014 ± 0.0005	0.008
JX	179.3 ± 15.5	<0.001	0.97 ± 0.21	<0.001	-0.0009 ± 0.0007	0.228
J	170.0 ± 22.0	<0.001	0.98 ± 0.32	0.002	-0.0008 ± 0.0011	0.456
			9 months of age			
F	155.9 ± 13.6	<0.001	0.79 ± 0.13	<0.001	-0.0002 ± 0.0003	0.547
FX	160.2 ± 11.6	<0.001	0.78 ± 0.12	<0.001	-0.0001 ± 0.0003	0.712
FJ	124.2 ± 14.5	<0.001	1.18 ± 0.15	<0.001	-0.0011 ± 0.0004	0.004
JX	154.4 ± 19.2	<0.001	0.88 ± 0.21	<0.001	-0.0005 ± 0.0006	0.422
J	128.5 ± 29.9	<0.001	1.07 ± 0.34	0.002	-0.0009 ± 0.0010	0.375
			12 months of age			
F	130.0 ± 15.4	<0.001	0.77 ± 0.12	<0.001	-0.0003 ± 0.0002	0.256
FX	145.7 ± 13.2	<0.001	0.67 ± 0.11	<0.001	0.0000 ± 0.0002	0.928
FJ	99.5 ± 16.5	<0.001	1.07 ± 0.14	<0.001	-0.0008 ± 0.0003	0.005
JX	112.9 ± 21.8	<0.001	0.99 ± 0.19	<0.001	-0.0007 ± 0.0004	0.071
J	63.8 ± 33.7	0.059	1.36 ± 0.31	<0.001	-0.0015 ± 0.0007	0.034
			15 months of age			
F	71.5 ± 19.2	<0.001	0.91 ± 0.12	<0.001	-0.0006 ± 0.0002	0.002
FX	84.1 ± 16.8	<0.001	0.87 ± 0.11	<0.001	-0.0005 ± 0.0002	0.007
FJ	45.4 ± 20.9	0.030	1.13 ± 0.14	<0.001	-0.0009 ± 0.0002	<0.001
JX	33.6 ± 27.0	0.213	1.27 ± 0.18	<0.001	-0.0012 ± 0.0003	<0.001
J	-4.0 ± 40.2	0.920	1.48 ± 0.30	<0.001	-0.0015 ± 0.0005	0.006
			18 months of age			
F	40.2 ± 23.3	0.085	0.87 ± 0.12	<0.001	-0.0005 ± 0.0001	0.0005
FX	2.4 ± 20.6	0.907	1.10 ± 0.11	<0.001	-0.0008 ± 0.0001	<0.001
FJ	5.5 ± 25.7	0.831	1.10 ± 0.14	<0.001	-0.0008 ± 0.0002	<0.001
JX	-12.2 ± 32.0	0.702	1.26 ± 0.18	<0.001	-0.0011 ± 0.0002	<0.001
J	-64.8 ± 45.3	0.152	1.53 ± 0.27	<0.001	-0.0014 ± 0.0004	<0.001
			21 months of age			
F	-33.5 ± 28.8	0.244	1.06 ± 0.13	<0.001	-0.0007 ± 0.0001	<0.001
FX	-78.6 ± 25.5	0.002	1.29 ± 0.12	<0.001	-0.0009 ± 0.0001	<0.001
FJ	-75.3 ± 31.6	0.017	1.31 ± 0.15	<0.001	-0.0009 ± 0.0002	<0.001
JX	-29.9 ± 39.0	0.433	1.15 ± 0.19	<0.001	-0.0008 ± 0.0002	<0.001
J	-191.9 ± 58.7	0.001	1.96 ± 0.31	<0.001	-0.0019 ± 0.0004	<0.001

[1]Where milksolids were calculated as the sum of milk fat and milk protein yields
[2]Where F is Holstein-Friesian, FX is Holstein-Friesian crossbred, FJ is Holstein-Friesian-Jersey crossbred, JX is Jersey crossbred and J is Jersey.
[3]P value tests that the corresponding regression coefficient is significantly different from zero.

The relationship between LWT and ECM yields for FJ heifers is depicted in Figure 3.1. It illustrates that the relationship is linear when heifers were three months of age, and curvilinear when heifers were six months of age and older. The ECM yield response to increasing LWT is greater in lighter heifers than heavier heifers aged six to 21 months of age, with no observed maximum response within the LWT range observed (Table 3.5).

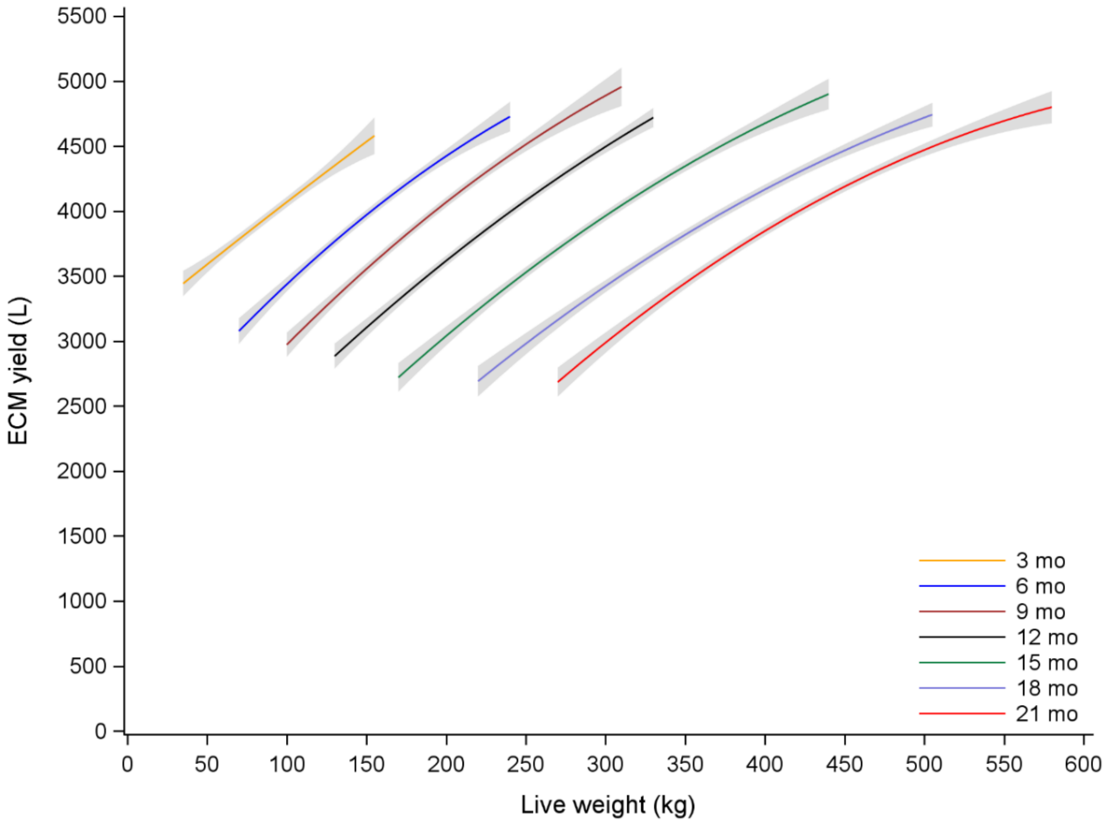

Figure 3.1 The relationship between live weight at 3, 6, 9, 12, 15, 18 and 21 months (mo) of age and energy-corrected milk (ECM) yield in first lactation Holstein-Friesian-Jersey crossbred (FJ) dairy heifers. The live weight range for each age is the range of live weights observed for that age group. Grey shading indicates 95% confidence intervals.

Table 3.5 Mean and range of live weight (LWT) of dairy heifers and the LWT at which the quadratic equation predicting the effect of LWT on first lactation (First) and accumulated three-parity (3-parity) energy-corrected milk (ECM) and milksolids (MS) yields reached a maximum (max.).

Breed group[1] and age (mo)	Mean LWT (kg)	Range (kg)	LWT (kg) at max. ECM		LWT (kg) at max. MS	
			First	3-parity	First	3-parity
F						
3	96.3	36.2 - 155.8	-[2]	-	-	-
6	161.3	69.0 - 247.3	-	275[3]	-	273
9	203.5	100.1 - 313.2	-	**312**[4]	-	**313**
12	255.7	125.8 - 383.6	-	**367**	-	**370**
15	326.8	194.3 - 472.1	776	**434**	758	**433**
18	403.6	237.4 - 564.0	840	**519**	870	**523**
21	447.5	291.1 - 612.5	804	**565**	757	**564**
FX						
3	91.8	36.3 - 152.7	-	-	-	-
6	155.8	68.5 - 243.4	-	-	-	-
9	196.7	96.9 - 294.3	-	391	-	391
12	246.1	129.4 - 359.7	-	410	-	408
15	313.1	184.8 - 454.4	921	**425**	870	**423**
18	387.0	232.3 - 535.7	710	**480**	688	**480**
21	432.9	260.4 - 580.0	717	**528**	717	**527**
FJ						
3	88.5	36.1 - 155.2	-	**145**	-	**142**
6	150.8	73.2 - 238.2	452	**229**	418	**227**
9	191.0	103.9 - 310.2	547	**290**	536	**287**
12	238.1	130.0 - 367.6	684	403	669	393
15	301.5	168.4 - 438.8	687	452	628	448
18	372.2	219.0 - 507.2	741	**493**	688	**487**
21	419.7	272.7 - 581.8	713	**526**	728	**523**
JX						
3	85.5	36.7 - 144.8	-	**116**	-	**114**
6	145.9	73.0 - 237.2	-	**217**	-	**213**
9	185.0	104.1 - 277.5	-	283	-	**276**
12	229.9	127.5 - 328.6	-	-	-	-
15	290.0	166.2 - 420.6	560	**416**	529	**410**
18	357.6	221.4 - 512.3	607	**442**	573	**436**
21	405.5	274.4 - 554.7	724	**486**	719	**483**
J						
3	81.0	36.7 - 143.2	146	-	**142**	-
6	136.2	73.9 - 225.4	-	-	-	-
9	173.4	99.6 - 262.0	-	-	-	**260**
12	214.7	131.0 - 308.2	-	**281**	453	**278**
15	268.2	170.6 - 380.1	521	**351**	493	**348**
18	329.4	211.3 - 457.3	562	**452**	546	**443**
21	378.2	260.0 - 505.3	547	**485**	516	**476**

[1]F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred

[2]Dashes indicate the quadratic effect was not significant (P>0.05), so no maximum was estimated

[3]Non-bolded values indicate a significant quadratic effect, but an estimated LWT outside of the LWT range observed

[4]Bolded values indicate a LWT at which maximum yield was estimated to occur within the LWT range observed

Jersey heifers had significant linear and quadratic effects for LWT at three months of age for ECM yields, whereas, F heifers had no significant relationship between LWT and ECM yields. Other breed groups (FX, FJ and JX) had a linear relationship between LWT and ECM yield (Table 3.3). In contrast, LWT at 21 months of age had significant linear and quadratic effects on ECM for all breed groups (Table 3.3). Based on the 95% confidence intervals, there were limited differences in ECM yield between heifers of differing breed groups when they were similar in LWT at 21 months of age. For example, 380 kg F heifers were estimated to produce 3,570 ± 21 kg ECM and 380 kg J heifers were estimated to produced similarly at 3,654 ± 23 kg. In addition, 450 kg 21-month-old heifers were estimated to produce 4,068 ± 19 kg and 4,057 ± 35 kg ECM for F and J, respectively. At the heavier end of the LWT range for J heifers (>430 kg) FJ and FX heifers produced more ECM than J heifers. In contrast, for LWT at three months of age J heifers produced less ECM at all LWTs compared with F, FX and FJ heifers, and for LWTs less than 125 kg produced less than JX heifers. All other breed groups produced similar quantities of ECM when they were similar in LWT at three months of age.

When the quadratic effect was significant, the first derivative of the equation was used to estimate at which LWT the maximum yield occurred (Table 3.5). At all ages studied, the LWT at which maximum ECM yields occurred were greater than the maximum LWT of heifers in the dataset. The maximum milksolids yield occurred for J heifers that were 142 kg at three months of age (maximum observed LWT was 143 kg). For all other breed groups and ages, the estimated LWT at which maximum milksolids yield was attained was greater than the LWT range studied.

3.4.3 Three-parity production

Out of the 67,833 cows for which three-parity production was reported, 44,851 (66.1%) had three lactations, 10,146 (15.0%) had first and second only lactation only and 12,836 (18.9%) had first lactation only.

Live weight from three to 21 months of age had significant linear and quadratic effects on three-parity milk production (Table 3.6 & Table 3.7). Similar to first lactation yields, heifers that were heavier produced more three-parity ECM and milksolids compared with heifers that were lighter. When significant, the linear effects were positive, and the quadratic effects were negative (Table 3.6 & Table 3.7). For FJ and JX heifers, there was always a relationship between LWT and three-parity milk production. Whereas for F, FX and J heifers there were some ages (three and six months of age) where no significant relationship existed (Table 3.6 & Table 3.7). Similar to the relationship with first lactation yields, the quadratic effects of LWT were more often significant at older ages (nine to 21 months of age) compared with younger ages (three and six months of age), except for FJ heifers where the relationship was always curvilinear (Table 3.6 & Table 3.7).

Table 3.6 Intercept and regression coefficients ± s.e. for the linear and quadratic effects of live weight (LWT) from three to 21 months of age of dairy heifers on accumulated three-parity energy-corrected milk (ECM) yield.

Breed group[1]	Intercept (kg ECM)	P value[2]	Linear (kg ECM/kg LWT)	P value	Quadratic (kg ECM/kg LWT^2)	P value
			3 months of age			
F	7,255.6 ± 1099.8	<0.001	43.80 ± 22.86	0.055	-0.1052 ± 0.1183	0.374
FX	7,611.8 ± 955.0	<0.001	40.02 ± 20.55	0.052	-0.0625 ± 0.1103	0.571
FJ	5,114.3 ± 1081.5	<0.001	92.01 ± 23.96	<0.001	-0.3183 ± 0.1324	0.016
JX	5,554.4 ± 1346.3	<0.001	89.89 ± 30.82	0.004	-0.3865 ± 0.1753	0.028
J	5,350.5 ± 1850.5	0.004	64.50 ± 44.26	0.145	-0.1521 ± 0.2637	0.564
			6 months of age			
F	1,911.7 ± 1398.7	0.172	76.66 ± 17.27	<0.001	-0.1393 ± 0.0530	0.009
FX	5,241.8 ± 1154.9	<0.001	41.33 ± 14.66	0.005	-0.0346 ± 0.0464	0.456
FJ	565.2 ± 1384.8	0.683	101.76 ± 18.09	<0.001	-0.2220 ± 0.0588	<0.001
JX	1,821.9 ± 1737.8	0.295	89.29 ± 23.49	<0.001	-0.2058 ± 0.0790	0.009
J	3,195.6 ± 2344.9	0.173	57.14 ± 33.57	0.089	-0.0766 ± 0.1197	0.523
			9 months of age			
F	-2,329.4 ± 1573.4	0.139	95.64 ± 15.48	<0.001	-0.1535 ± 0.0379	<0.001
FX	1,902.2 ± 1359.5	0.162	61.23 ± 13.76	<0.001	-0.0782 ± 0.0347	0.024
FJ	-1,437.1 ± 1681.1	0.393	96.43 ± 17.56	<0.001	-0.1664 ± 0.0456	<0.001
JX	-239.9 ± 2165.1	0.912	86.25 ± 23.39	<0.001	-0.1524 ± 0.0628	0.015
J	-2,502.5 ± 3151.9	0.427	104.59 ± 35.86	0.004	-0.1986 ± 0.1015	0.051
			12 months of age			
F	-4,652.8 ± 1753	0.008	92.87 ± 13.82	<0.001	-0.1265 ± 0.0271	<0.001
FX	-544.8 ± 1573.3	0.729	66.79 ± 12.81	<0.001	-0.0815 ± 0.0260	0.002
FJ	-837.0 ± 1904.8	0.660	69.90 ± 16.08	<0.001	-0.0868 ± 0.0338	0.010
JX	-177.6 ± 2430.8	0.942	65.84 ± 21.27	0.002	-0.0849 ± 0.0463	0.067
J	-8,073.9 ± 3625.2	0.026	133.99 ± 33.55	<0.001	-0.2381 ± 0.0773	0.002
			15 months of age			
F	-7,900.7 ± 2197.6	<0.001	91.90 ± 13.56	<0.001	-0.1058 ± 0.0208	<0.001
FX	-6,014.1 ± 1996.5	0.003	85.97 ± 12.79	<0.001	-0.1011 ± 0.0204	<0.001
FJ	-4,245.1 ± 2415.8	0.079	75.28 ± 16.11	<0.001	-0.0832 ± 0.0268	0.002
JX	-3,999.4 ± 3012.7	0.184	76.65 ± 20.86	<0.001	-0.0922 ± 0.0360	0.010
J	-10,900.0 ± 4200.8	0.010	123.99 ± 31.20	<0.001	-0.1766 ± 0.0577	0.002
			18 months of age			
F	-9,241.3 ± 2704.6	0.001	81.15 ± 13.50	<0.001	-0.0782 ± 0.0168	<0.001
FX	-11,435.0 ± 2400.1	<0.001	97.14 ± 12.45	<0.001	-0.1012 ± 0.0161	<0.001
FJ	-9,131.0 ± 2929.1	0.002	86.50 ± 15.82	<0.001	-0.0878 ± 0.0213	<0.001
JX	-10,465.0 ± 3599.0	0.004	98.46 ± 20.17	<0.001	-0.1114 ± 0.0282	<0.001
J	-10,302.0 ± 4743.2	0.030	94.88 ± 28.68	<0.001	-0.1050 ± 0.0432	0.015
			21 months of age			
F	-13,611.0 ± 3437.6	<0.001	90.09 ± 15.40	<0.001	-0.0797 ± 0.0172	<0.001
FX	-16,205.0 ± 3004.2	<0.001	106.40 ± 13.91	<0.001	-0.1007 ± 0.0161	<0.001
FJ	-14,907.0 ± 3602.3	<0.001	102.33 ± 17.24	<0.001	-0.0973 ± 0.0206	<0.001
JX	-15,949.0 ± 4482.9	<0.001	111.97 ± 22.21	<0.001	-0.1153 ± 0.0274	<0.001
J	-16,524.0 ± 6454.1	0.011	113.09 ± 34.15	<0.001	-0.1167 ± 0.0450	0.010

[1]Where F is Holstein-Friesian, FX is Holstein-Friesian crossbred, FJ is Holstein-Friesian-Jersey crossbred, JX is Jersey crossbred and J is Jersey.
[2]P value tests that the corresponding regression coefficient is significantly different from zero.

Table 3.7 Intercept and regression coefficients ± s.e. for the linear and quadratic effects of live weight (LWT) from three to 21 months of age of dairy heifers on accumulated three-parity milksolids[1] (MS) yield.

Breed group[2]	Intercept (kg MS)	P value[3]	Linear (kg MS/kg LWT)	P value	Quadratic (kg MS/kg LWT^2)	P value
			3 months of age			
F	559.8 ± 84.6	<0.001	3.26 ± 1.76	0.064	-0.0083 ± 0.0091	0.364
FX	594.5 ± 73.5	<0.001	2.89 ± 1.58	0.067	-0.0045 ± 0.0085	0.600
FJ	397.3 ± 83.2	<0.001	7.08 ± 1.84	<0.001	-0.0250 ± 0.0102	0.014
JX	434.6 ± 103.6	<0.001	6.94 ± 2.37	0.003	-0.0305 ± 0.0135	0.024
J	406.6 ± 142.4	0.004	5.26 ± 3.40	0.122	-0.0135 ± 0.0203	0.506
			6 months of age			
F	156.3 ± 107.6	0.146	5.73 ± 1.33	<0.001	-0.0105 ± 0.0041	0.010
FX	407.5 ± 88.8	<0.001	3.11 ± 1.13	0.006	-0.0026 ± 0.0036	0.464
FJ	37.7 ± 106.5	0.723	7.94 ± 1.39	<0.001	-0.0175 ± 0.0045	<0.001
JX	141.3 ± 133.7	0.290	6.94 ± 1.81	<0.001	-0.0163 ± 0.0061	0.008
J	241.9 ± 180.4	0.180	4.55 ± 2.58	0.078	-0.0064 ± 0.0092	0.486
			9 months of age			
F	-160.8 ± 121.0	0.184	7.13 ± 1.19	<0.001	-0.0114 ± 0.0029	<0.001
FX	155.0 ± 104.6	0.138	4.61 ± 1.06	<0.001	-0.0059 ± 0.0027	0.028
FJ	-118.0 ± 129.3	0.362	7.52 ± 1.35	<0.001	-0.0131 ± 0.0035	<0.001
JX	-31.3 ± 166.6	0.851	6.84 ± 1.80	<0.001	-0.0124 ± 0.0048	0.011
J	-205.9 ± 242.5	0.396	8.28 ± 2.76	0.003	-0.0159 ± 0.0078	0.042
			12 months of age			
F	-327.6 ± 134.9	0.015	6.88 ± 1.06	<0.001	-0.0093 ± 0.0021	<0.001
FX	-22.7 ± 121.0	0.852	4.98 ± 0.99	<0.001	-0.0061 ± 0.0020	0.002
FJ	-66.0 ± 146.5	0.652	5.42 ± 1.24	<0.001	-0.0069 ± 0.0026	0.008
JX	-22.9 ± 187.0	0.903	5.21 ± 1.64	0.002	-0.0069 ± 0.0036	0.052
J	-643.1 ± 278.9	0.021	10.58 ± 2.58	<0.001	-0.0190 ± 0.0059	0.001
			15 months of age			
F	-557.0 ± 169.1	0.001	6.75 ± 1.04	<0.001	-0.0078 ± 0.0016	<0.001
FX	-430.4 ± 153.6	0.005	6.43 ± 0.98	<0.001	-0.0076 ± 0.0016	<0.001
FJ	-325.4 ± 185.9	0.080	5.83 ± 1.24	<0.001	-0.0065 ± 0.0021	0.002
JX	-310.7 ± 231.8	0.180	5.99 ± 1.61	<0.001	-0.0073 ± 0.0028	0.008
J	-874.3 ± 323.2	0.007	9.87 ± 2.40	<0.001	-0.0142 ± 0.0044	0.001
			18 months of age			
F	-652.7 ± 208.1	0.002	5.96 ± 1.04	<0.001	-0.0057 ± 0.0013	<0.001
FX	-840.5 ± 184.7	<0.001	7.30 ± 0.96	<0.001	-0.0076 ± 0.0012	<0.001
FJ	-705.1 ± 225.4	0.002	6.72 ± 1.22	<0.001	-0.0069 ± 0.0016	<0.001
JX	-809.4 ± 276.9	0.004	7.67 ± 1.55	<0.001	-0.0088 ± 0.0022	<0.001
J	-850.7 ± 365.0	0.020	7.71 ± 2.21	<0.001	-0.0087 ± 0.0033	0.009
			21 months of age			
F	-983.7 ± 264.5	<0.001	6.66 ± 1.19	<0.001	-0.0059 ± 0.0013	<0.001
FX	-1,203.2 ± 231.2	<0.001	8.01 ± 1.07	<0.001	-0.0076 ± 0.0012	<0.001
FJ	-1,153.9 ± 277.2	<0.001	7.95 ± 1.33	<0.001	-0.0076 ± 0.0016	<0.001
JX	-1,232.4 ± 344.9	<0.001	8.70 ± 1.71	<0.001	-0.0090 ± 0.0021	<0.001
J	-1,361.0 ± 496.6	0.006	9.23 ± 2.63	<0.001	-0.0097 ± 0.0035	0.005

[1]Where milksolids were calculated as the sum of milk fat and milk protein yields

[2]Where F is Holstein-Friesian, FX is Holstein-Friesian crossbred, FJ is Holstein-Friesian-Jersey crossbred, JX is Jersey crossbred and J is Jersey.

[3]P value tests that the corresponding regression coefficient is significantly different from zero.

In contrast to first lactation yields, for all breeds, the majority of ages studied had a LWT at which maximum three-parity yields were achieved within the LWT range studied (Table 3.5). All of which were greater than the mean LWT and closer to the heavier end of the LWT range (Table 3.5). For example, the LWT of 21-month-old FJ heifers at which maximum ECM and milksolids yields were estimated to occur at was more than 90 kg heavier than the mean LWT of 420 kg, and nearer to the maximum LWT observed of 582 kg (Table 3.5).

The relationship between LWT and three-parity ECM yields for FJ heifers is depicted in Figure 3.2 It illustrates that the relationship is curvilinear for all ages. For heifers aged 12- and 15-months-old, the ECM yield response to increasing LWT was greater in lighter heifers than heavier heifers, with no observed maximum within the LWT range studied Figure 3.2 & Table 3.5). For all other ages, the ECM yield response to increasing LWT was greater in lighter heifers than heavier heifers, up to a maximum (145, 229, 290, 493 and 526 kg, respectively for three, six, nine, 18 and 21 months of age Figure 3.2 & Table 3.5).

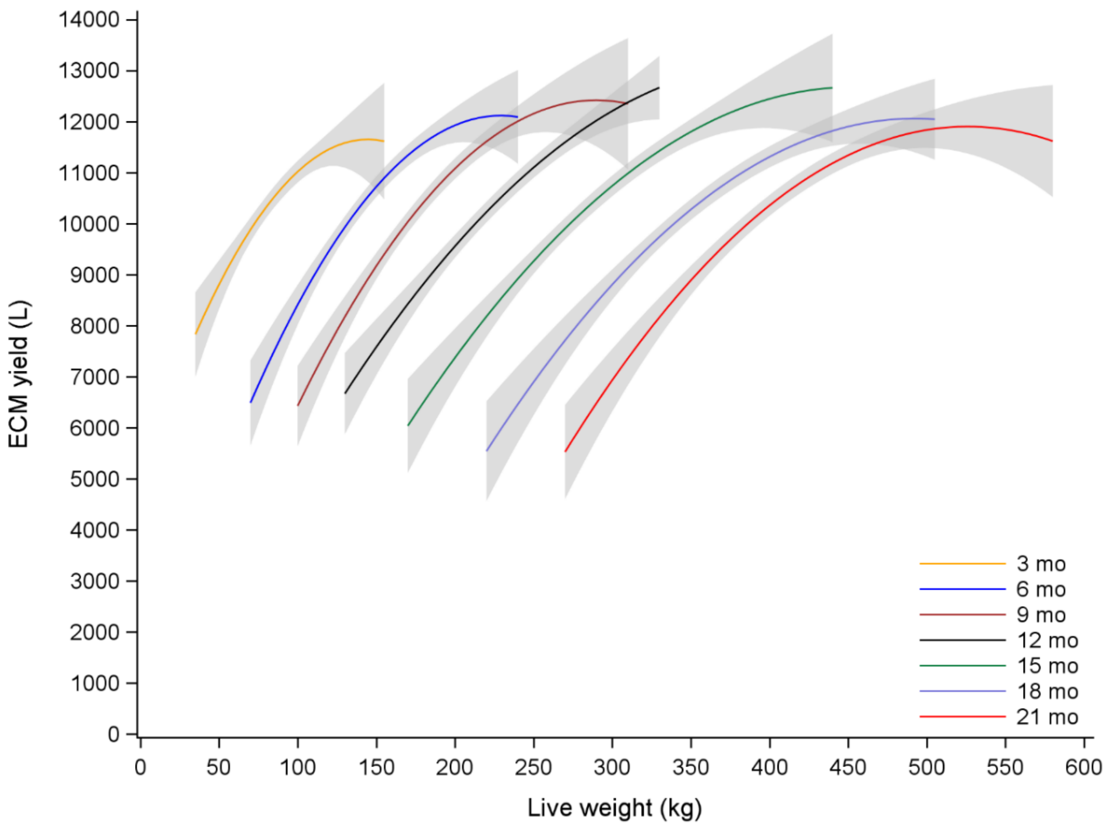

Figure 3.2 The relationship between live weight at 3, 6, 9, 12, 15, 18 and 21 months (mo) of age and three-parity energy-corrected milk (ECM) yield for Holstein-Friesian-Jersey crossbred (FJ) dairy heifers. The live weight range for each age is the range of live weights observed for that age group. Grey shading indicates 95% confidence intervals.

Similar to first lactation, LWT at 21 months of age had significant linear and quadratic effects on three-parity ECM yield for all breed groups (Table 3.5). Due to the significant quadratic effects for all breed groups, there were LWTs at which maximum ECM yields were attained within the LWT range studied (Table 3.5). These were observed at 565, 528, 526, 486 and 485 kg, for F, FX, FJ, JX, and J respectively; all at the heavier end of the LWT range studied. Based on the 95% confidence intervals, there were no differences in milk yield among the breed groups for the majority of LWTs at 21 months of age. From 325 to 435 kg, 335 to 485 kg, and 365 to 470 kg, respectively JX, FJ and FX heifers produced more ECM yields than F heifers. Outside of these ranges, breed groups produced similar quantities of ECM.

3.5 Discussion

The relationship between precalving LWT and milk production for New Zealand dairy heifers was predominantly curvilinear. Heifers that were heavier produced more milk in first lactation and three-parity lactations than heifers that were lighter, and the response to an increase in LWT was greater for lighter heifers compared with heavier heifers. This indicates there could be greater milk production benefits of preferentially feeding lighter heifers to attain heavier precalving LWTs.

Previous studies have reported positive relationships between precalving LWTs and first lactation milk production but have only reported linear effects (Dobos et al. 2001; McNaughton & Lopdell 2013; van der Waaij et al. 1997; Van Eetvelde et al. 2017). Similarly, Van Amburgh et al. (1998) reported a positive relationship between post-calving LWT and first lactation milk production. The current study included linear and quadratic effects to test if there was a limit as to how heavy heifers can be before their milk production performance was limited. The results from the present study indicate that for F, FX, FJ and JX, there was no LWT within the range studied where a maximum first lactation yield was achieved; an increase in LWT at each age was associated with an increase in milk production. For J heifers in the current study, there was only one age where a maximum was identified within the LWT range observed; 3 months of age for milksolids yield. In contrast, first lactation Australian Holstein-Friesian heifers had estimated maximum milk, protein and fat yields when they were 559, 563 and 568 kg respectively between 24 and 33 months of age (Dobos et al. 2001). The LWTs reported by Dobos et al. (2001) at which maximum milk, protein and fat yields occurred at were similar to the LWTs at which maximum three-parity milk production were estimated at in the current study for 21-month-old F, FX and FJ heifers.

Similar to first lactation analyses, previous studies have reported positive linear relationships between precalving LWTs and second lactation (McNaughton & Lopdell 2013; van der Waaij et al. 1997) and third lactation milk production (van der Waaij et al. 1997), but have also only reported linear effects. In addition to not considering quadratic effects, there is a potential bias from considering only cows that survived to lactate each year if particular cows had better survival than others. The data in the current study for three-parity production includes all heifers that were old enough to have completed three lactations, regardless of whether they did or not.

Based on their first lactation production and results from previous studies (Lembeye et al. 2016; Macdonald et al. 2005), the mean three-parity yields for the breed groups is less than expected if only cows that had completed all three lactations were included. This reflects that approximately 34% of the 67,833 heifers in the current study for three-parity yields failed to complete all three lactations. The costs of rearing a heifer are incurred regardless of how long she remains in the herd. Including the heifers that did not complete all three lactations describes the effect that LWT of replacement heifers has on accumulated milk yields without discriminating whether the increased milk yield came from greater survival or from greater production per surviving cow. It is possible that the lighter heifers in the current study only survived one or two lactations and hence their three-parity milk yields were much lower than the heavier heifers that survived to complete two or three lactations. Nevertheless, the relationships between precalving LWTs and milk yield per day was consistent with the results reported here for first lactation and three-parity yields (Appendix II).

Analysing the relationship including only the survivors does not truly describe the impact of light heifers on milk production, as it does not take into account how long the heifers actually remained productive for, in addition to the decreased milk production (Archer et al. 2013). Further research on the relationships between LWT and survival of heifers is required to confirm this but could explain why the relationship between LWT and three-parity milk yields was more curvilinear than the relationship between LWT and first lactation milk production.

There are few studies that have analysed milk production accumulated over multiple lactations, the majority of which included data only from surviving cows (Archer et al. 2013; Bettenay 1985; Heinrichs & Heinrichs 2011; Hutchison et al. 2017; Lin et al. 1988; Soberon et al. 2012). Of these studies there were only two that examined the relationship between LWT and accumulated milk production over multiple lactations (Bettenay 1985; Heinrichs & Heinrichs 2011), both of which concluded that there was no relationship between LWT and milk yield. The study by Heinrichs and Heinrichs (2011) included multiple fixed effects such as age at first calving and age at weaning, which might have been confounded with LWT at first calving. This may explain why they observed no relationship between LWT and lifetime milk yields. In the current study, no such potential confounding effects were included in the models. Bettenay (1985) had a small sample size of 18 heifers per treatment when comparing four ages and two LWTs at breeding. After breeding, heifers were run together, allowing the smaller heifers to grow faster and catch up to the larger heifers (Bettenay 1985). Additionally, only heifers that completed all four lactations were used to estimate accumulated yield over four lactations. As discussed previously this method does not fully estimate the milk production impact of the heifers that did not survive for all lactations (Archer et al. 2013).

For the heifers in the current study, the periods of slowest growth occurred between 5 and 12 months of age and between 20 and 22 months of age (Chapter 2). The slow growth over these periods is similar to what has been reported previously in New Zealand dairy heifers (McNaughton & Lopdell 2012). This slow growth corresponded to heifers being the furthest from target LWT when they were 12 and 22 months of age (Handcock et al. 2016). For first lactation, the 12-month LWTs at which maximum yields were attained in the current study were outside of the range studied. The 12-month LWTs at which maximum three-parity yields were attained were either outside of the range studied or nearer the upper limit of the range studied. These results suggest that heifers may benefit from increased pasture allowances or supplementary feeding to improve growth rates leading up to 12 months of age, with even greater benefits from feeding the lighter heifers.

To the author's knowledge, this is the first study that has compared milk production of Holstein-Friesians, Jerseys and various proportions of Holstein-Friesian and Jersey at similar LWTs. Overall the five breed groups studied produced differing quantities of milk, however, throughout the majority of LWTs studied, heifers of differing breed makeup produced similar quantities of milk when they were the same LWT precalving. These results suggest that a large proportion of the milk production advantage that F heifers have over J heifers may be due to F heifers being heavier than J heifers (Chapter 2). In the current study, the average LWT of 21-month-old J heifers was approximately 380 kg. The predicted first lactation ECM yield for 380 kg J was 3,654 L, similar to 380 kg F heifers that produced 3,570 L. A reason these estimates were similar may be due to how "well-grown" or close to mature LWT the heifers were. The average mature LWT of New Zealand cattle is 420 kg and 510 kg, for J and F respectively (Livestock Improvement Corporation & DairyNZ 2017). The target LWT at 21 months of age is around 90% mature LWT (Troccon 1993; Wathes et al. 2014). Based on the above estimates of mature LWT, a 380 kg 21-month-old J heifer would be considered well-grown (90% mature LWT), whereas a 380 kg F heifer would be considered poorly grown (75% mature LWT). The mean first lactation ECM yield of F heifers was 3,971 L, much greater than the predicted first lactation ECM production of a 380 kg F heifer. Furthermore, the mean first lactation ECM yield of J heifers was 3,695 L, similar to the predicted first lactation ECM production of a 380 kg J heifer. There was a positive relationship between percentage of target LWT and milk production of New Zealand heifers (McNaughton & Lopdell 2013), therefore, we would expect the poorly grown F heifer to produce below average for F, whereas the well-grown J heifer to produce near average for J.

An alternative reason F and J heifers produced similar quantities of milk when they were similar in LWT may be due to the considerable variation in LWT within each breed group of the current study, suggesting there may be considerable variation in mature LWT within each breed group as well. In the study by Archbold et al. (2012), there was a strong linear relationship between LWT at 15 months of age and mature LWT; the heifers that were heavier at 15 months of age were also heavier at maturity. Therefore, the heifers that were lighter at 21 months of age in the current study may have been lighter at maturity compared with heifers that were heavier at 21 months of age. Due to the low numbers of LWT records of mature in-milk cows in the Livestock Improvement Corporation database, this hypothesis was unable to be confirmed. However, there is considerable variation in LWT breeding values (which are estimates of mature LWT) within Friesian (-33.3 – 104.7 kg), Jersey (-85.5 – -6 kg) and Friesian-Jersey crossbred bulls (-51.3 – 51.9 kg) (DairyNZ 2018f). Future work should be directed at understanding the relationship between heifer LWT, LWT breeding values and mature LWT in the New Zealand system. These results show the potential to increase milk production of New Zealand dairy heifers by increasing LWTs during the rearing phase. Further research on the growth pattern necessary to achieve heavier LWTs is required.

3.6 Conclusions

There was a positive curvilinear relationship between LWT and milk production in the first lactation and three-parity lactations. Heifers that were heavier produced more milk than heifers that were lighter, regardless of breed group. Consequently, for heifers that were average and below average in LWT, there would be considerable milk production benefits over the first 3 lactations by improving rearing practices to result in heavier heifers throughout the precalving rearing phase.

Chapter 4 Increased growth in first year of life is more beneficial to milk production of dairy heifers compared with growth in the second year

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4.1 Abstract

Previous research has indicated that greater milk production could be achieved in first and subsequent lactations by growing dairy heifers to reach greater live weights (LWTs) during rearing. However, it is not known what the effect of different growth rate trajectories is on milk production, provided the heifers achieve similar LWT prior to first calving. The aim of the current study was to determine the effect of differences in growth up to 12 and 21 months of age on milk production over multiple lactations. Live weight and milk production records were available for heifers in first lactation (n=140,113) and accumulated three-parity milk production (n=67,833). Heifers were classified into five breed groups; Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Jersey (J), Jersey crossbred (JX) and Holstein-Friesian-Jersey crossbred (FJ). Within each breed group heifers were grouped into quintiles for LWT at 21 months of age (tiny, small, average, big and huge). The percentage of 21-month LWT achieved at 12 months of age (pctLWT21) was calculated by dividing each heifer's 12-month LWT by her 21-month LWT. Heifers that demonstrated a large proportion of growing in their first year (up to 12 months of age), and hence were a greater pctLWT21 produced more milk during first and three-parity lactation than heifers that did a lower proportion of their growing during their first year (were a lesser pctLWT21). For FJ heifers that were average in LWT at 21 months of age, those that were 45% of pctLWT21 produced 3,741.3 ± 34.3 L of ECM in first lactation, less than those that were 55% of pctLWT21 (3,942.8 ± 21.4 L), and less than those that were 65% of pctLWT21 (4,144.9 ± 27.0 L). The effect of being a greater pctLWT21 was more pronounced on first lactation milk yields compared with three-parity milk yields. These results indicate that increased growth in early life is beneficial to future milk production.

4.2 Introduction

Positive relationships between precalving LWT and milk production have been reported for New Zealand dairy heifers (McNaughton & Lopdell 2013; van der Waaij et al. 1997). These results indicated that greater milk production could be achieved in the first and subsequent lactations by growing heifers to reach greater LWTs.

To ensure heifers are well grown, the recommended target LWTs are 30% of mature LWT at six months of age, 60% at 15 months (mating) and 90% at 22 months (pre-calving) (Troccon 1993; Wathes et al. 2014). Targets are applied across all breeds, assuming that mature LWT is known. Recommended growth between the three target LWTs is predominantly linear. However, heifer growth in a seasonal pasture-based system does not follow the linear trajectory that the target LWTs require (Chapter 2).

The periods of slowest growth of heifers has been demonstrated to occur between five and 12 months of age and between 20 and 22 months of age (Chapter 2). The slow growth over these periods is similar to what has been reported previously in New Zealand dairy heifers (McNaughton & Lopdell 2012). This slow growth corresponded to heifers being the furthest from target LWT when they were 12 and 22 months of age (Handcock et al. 2016). It is not known what effect a seasonal growth rate pattern rather than a linear trajectory has on future milk production. Previous research has suggested that heifers may benefit from increased pasture allowances or supplementary feeding to improve growth rates leading up to 12 months of age, especially the lighter heifers (Chapter 3).

Results from a Norwegian study reported that there was a significant relationship between growth rate from 10 to 15 months of age and first lactation milk production of Norwegian Red heifers (Storli et al. 2017). However, the study by Storli et al. (2017) did not report differences in growth pattern between ages, provided the heifers ended up similar in LWT. Previous results indicated that heifers that were heavier at any age produced more milk than heifers that were lighter (Chapter 3), however, it is unknown if the milk production advantage from being heavier at the younger ages (e.g. 12 months of age) reflected the heifer being more likely to be heavier at later ages (e.g. 21 months of age).

The aim of the current study was to determine the effect of differences in growth pattern up to 12 months and 21 months of age on milk production over multiple lactations.

4.3 Materials and methods

4.3.1 Initial dataset

The initial dataset was extracted from the Livestock Improvement Corporation national dairy database and consisted of 189,936 spring-born heifers born between 2006-07 and 2013-14 spring-calving dairy seasons and located in 1,547 herds throughout New Zealand (Chapter 2). Using the regression coefficients from the growth curves generated in Chapter 2, LWTs were predicted for each heifer at three-monthly increments from three to 21 months of age in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Absolute growth rates (AGR) for each three-monthly increment were calculated as (LWT_2 – LWT_1) / (t_2 – t_1). Where t_1 is the initial age in days, t_2 is the final age in days, and LWT_1 and LWT_2 are the corresponding predicted LWTs at these ages (Fitzhugh & Taylor 1971)

Heifers were grouped into quintiles for LWT at 21 months of age (tiny, small, average, big and huge), within breed group, using the RANK procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The proportion of LWT achieved at 12 months of age with respect to LWT at 21 months of age (pctLWT21) was calculated for each animal.

Breed composition (expressed in 16th) based on pedigree information was used to classify heifers into one of five breed groups; Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Jersey (J), Jersey crossbred (JX) or Holstein-Friesian-Jersey crossbred (FJ). The criteria used to classify breed groups is outlined in Table 4.1. All heifers in the dataset were 16/16 pedigree recorded and were no more than 2/16 of any breed other than Holstein-Friesian or Jersey.

4.3.2 First lactation dataset

Data of calving dates and milk production records were extracted from the Livestock Improvement Corporation database and merged with growth curves of the 189,936 heifers as described in Chapter 3 to create the dataset for first lactation. Briefly, heifers were selected that had a first calving between June and December as two-year-olds (n=175,142). Heifers with a first lactation length of less than 80 days were excluded, additionally, records outside of the following limits were also excluded: 30 – 300 kg of milk protein, 40 – 400 kg of milk fat, 800 – 8000 L of milk yield. Lactations that were greater than 305 days were truncated at 305 days. This resulted in 140,113 heifers with suitable first-lactation records located in 1,326 herds (Table 4.1).

4.3.3 Three-parity production dataset

The dataset used for "First-lactation" analysis was merged with second and third calving dates and milk production records that were extracted from the Livestock Improvement Corporation database (2008/09 to 2016/17 spring-calving dairy seasons) as described in Chapter 3. Heifers born after the 2012/13 spring-calving dairy season (n=50,584) were removed from the dataset as at the time of data extraction they were not old enough to have had three full lactations. Heifers with a calving date but no milk yields (n=12,445) were removed from the dataset due to not knowing whether they were not herd tested or if they did not lactate. Second and third lactation yields were subject to the same criteria as first lactation yields.

Three-parity production was calculated as the sum of up to the first three lactations milk, fat or protein yields. Three-parity production was equivalent to first-parity production for heifers that did not have a recorded second calving date. Likewise, three-parity production was equivalent to the sum of first- and second-parity production for heifers that did not have a recorded third calving date. After these data edits there were 67,833 heifers remaining in the dataset that during first lactation were located in one of 910 herds (Table 4.1).

Table 4.1 Breed composition and number of records (N) for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) and Jersey (J) heifers included in the liveweight (LWT), first lactation (First) and accumulated three-parity production (3-parity) datasets.

Breed group	Breed composition	N (LWT)	N (First)	N (3-parity)*
F	F ≥ 14/16	47,852	34,936	16,382
FX	10/16 ≤ F ≤ 13/16	62,310	46,690	22,192
FJ	F < 10/16 and J < 10/16	42,842	31,373	15,154
JX	10/16 ≤ J ≤ 13/16	24,184	17,395	8,672
J	J ≥ 14/16	12,352	9,719	5,433
Total	-	189,936	140,113	67,833

*Only heifers born between spring 2006/07 and spring 2012/13 were included for three-parity analysis.

4.3.4 Data handling

The energy-corrected milk (ECM) yield formula used was from Beever and Doyle (2007), and derived from Tyrell and Reid (1965) and calculated as follows:

ECM = milk yield × (383 × fat percentage + 242 × protein percentage + 783.2)/3,140

Milksolids were calculated as the sum of milk fat and milk protein yields (lactose not included).

4.3.5 Statistical analysis

Least squares means for each combination of breed group and LWT category for LWT, pctLWT21 and milk yields were obtained using mixed models in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

The models for LWT and pctLWT21 included the fixed effects of breed group (F, FX, FJ, JX, J), LWT category (tiny, small, average, big, huge) within breed group, the covariate deviation from median date of birth (within herd-year), and the random effect of herd-year. Herd-year was defined as the herd and year at which the heifer was born.

The relationships between pctLWT21 and absolute growth rates at three-monthly intervals from three to 21 months of age were estimated using the same mixed model as described above but included the linear effect of pctLWT21 within breed group and LWT category.

The model for the analysis of first lactation and three-parity milk yields included the fixed effect of breed group, LWT category nested within breed group, the covariate deviation from median date of first calving (within herd-year contemporary group), and the random effect of herd-year contemporary group. Herd-year was defined as the herd and year at which the animal started the lactation.

The effects of pctLWT21 on first lactation and three-parity production were estimated using the same mixed model as described above but including the linear and quadratic effects of pctLWT21 nested within each combination of breed group and LWT category.

The solutions of regression coefficients from the mixed models were then used to predict ECM or milksolids production for heifers at different proportions of 21-month LWT at 12 months of age. Confidence intervals at the 95% level ($\mu \pm 1.96$ standard error) were used to test for differences.

4.4 Results

4.4.1 Live weight category performance

Number of heifers in each breed group-LWT category are given in Table 4.2 along with the mean and range in 21-month LWT in each LWT category. Heifers that were larger at 21 months of age were a lesser ($P<0.01$) proportion of their 21-month LWT when they were 12 months of age compared with heifers that were smaller at 21 months of age (Table 4.2).

The relationships between pctLWT21 and absolute growth rates were positive from three to 12 months of age and negative from 12 to 21 months of age. Mean growth rates at three-monthly intervals from three to 21 months of age are displayed for FJ heifers that were average in 21-month LWT and were 45, 55 or 65% pctLWT21 in Figure 4.1. Heifers that were further from their 21-month LWT at 12 months of age grew slower from three to 12 months of age than heifers that were closer to the 21-month LWT. From 12 to 21 months of age, this trend reversed with heifers that were a lesser pctLWT21 growing faster than heifers that were a greater pctLWT21 (Figure 4.1). In addition, heifers that were further from their 21-month LWT at 12 months of age exhibited greater fluctuations in AGR compared with heifers that were closer to their 21-month LWT at 12 months of age (Figure 4.1). For example, the AGR from six to nine months of age was 0.22 kg/d for FJ heifers that were 45% of their 21-month LWT, whereas, the AGR from 15 to 18 months of age was 0.99 kg/d for the same heifers (Figure 4.1). In contrast, the AGR from six to nine and 15 to 18 months of age was 0.59 and 0.61 kg/d for FJ heifers that were 65% of their 21-month LWT (Figure 4.1). The relationships between pctLWT21 and AGR for heifers of all breed groups and 21-month LWT categories followed similar trends to that displayed in Figure 4.1 (Appendix III).

Table 4.2 Number of records (N), range and least-squares means ± SEM of 21-month live weight (21m LWT) and proportion of 21m LWT at 12 months of age (pctLWT21) for heifers that were tiny, small, average, big or huge at 21 months of age within each breed group[1].

Breed group and LWT category	N	21m LWT range (kg)	21m LWT (kg)	pctLWT21 (%)
F				
Tiny	9,605	<416	$395.8^{a} \pm 0.2$	$57.8^{e} \pm 0.1$
Small	9,603	416 to 436	$426.0^{b} \pm 0.2$	$56.9^{d} \pm 0.1$
Average	9,606	436 to 453	$443.7^{c} \pm 0.2$	$56.7^{c} \pm 0.1$
Big	9,607	453 to 475	$461.5^{d} \pm 0.2$	$56.4^{b} \pm 0.1$
Huge	9,605	>475	$492.5^{e} \pm 0.2$	$55.6^{a} \pm 0.1$
FX				
Tiny	12,480	<403	$385.0^{a} \pm 0.2$	$57.9^{e} \pm 0.1$
Small	12,479	403 to 423	$413.7^{b} \pm 0.2$	$57.1^{d} \pm 0.1$
Average	12,478	423 to 440	$430.7^{c} \pm 0.2$	$56.8^{c} \pm 0.1$
Big	12,483	440 to 459	$447.6^{d} \pm 0.2$	$56.6^{b} \pm 0.1$
Huge	12,480	>459	$477.1^{e} \pm 0.2$	$56.0^{a} \pm 0.1$
FJ				
Tiny	8,578	<392	$374.7^{a} \pm 0.2$	$58.1^{e} \pm 0.1$
Small	8,575	392 to 411	$402.0^{b} \pm 0.2$	$57.2^{d} \pm 0.1$
Average	8,580	411 to 426	$418.2^{c} \pm 0.2$	$56.8^{c} \pm 0.1$
Big	8,576	426 to 445	$434.3^{d} \pm 0.2$	$56.5^{b} \pm 0.1$
Huge	8,576	>445	$462.0^{e} \pm 0.2$	$56.0^{a} \pm 0.1$
JX				
Tiny	4,843	<378	$360.9^{a} \pm 0.2$	$58.4^{e} \pm 0.1$
Small	4,844	378 to 398	$389.1^{b} \pm 0.2$	$57.1^{d} \pm 0.1$
Average	4,844	398 to 414	$405.8^{c} \pm 0.2$	$56.6^{c} \pm 0.1$
Big	4,844	414 to 433	$422.5^{d} \pm 0.2$	$56.2^{b} \pm 0.1$
Huge	4,843	>433	$450.3^{e} \pm 0.2$	$55.9^{a} \pm 0.1$
J				
Tiny	2,481	<351	$337.8^{a} \pm 0.3$	$58.7^{e} \pm 0.1$
Small	2,481	351 to 370	$363.2^{b} \pm 0.3$	$57.0^{d} \pm 0.1$
Average	2,482	370 to 387	$379.5^{c} \pm 0.3$	$56.3^{c} \pm 0.1$
Big	2,481	387 to 408	$397.2^{d} \pm 0.3$	$55.7^{b} \pm 0.1$
Huge	2,482	>408	$425.3^{e} \pm 0.3$	$54.7^{a} \pm 0.1$

[a-d] Values within a breed group and LWT category with different superscripts differ at P<0.01.

[1]F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

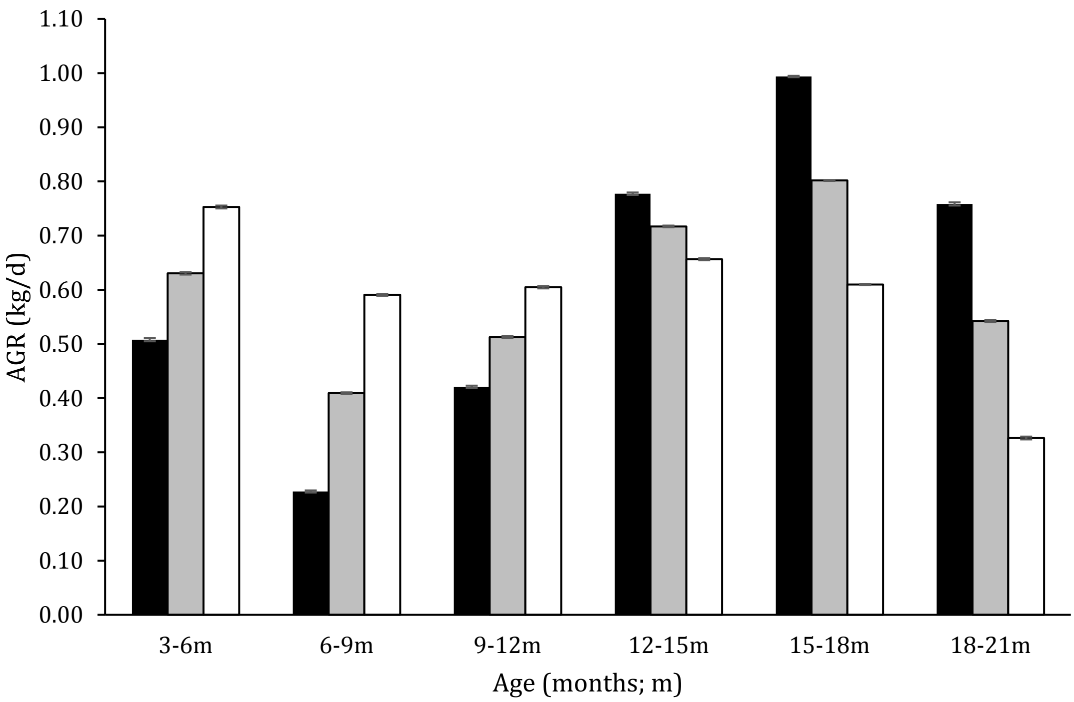

Figure 4.1 Predicted absolute growth rate (AGR; kg/d) in three-monthly increments from three to 21 months of age of Holstein-Friesian-Jersey heifers that were average in live weight at 21 months of age and were 45% (black), 55% (grey) or 65% (white) of their 21-month LWT at 12 months of age. Error bars indicate standard error of the mean.

4.4.2 First lactation milk production

Heifers of all breed groups that were smaller at 21 months of age produced less ($P<0.001$) ECM and milksolids in their first lactation than heifers of the same breed group that were larger (Table 4.3). For example, tiny FJ heifers produced 3653.8 kg of ECM, 5% less than that of small FJ heifers and 8%, 10% and 14% less than that of average, big and huge FJ heifers, respectively (Table 4.3).

Within each breed group-LWT category, heifers that were a greater proportion of their 21-month LWT at 12 months of age produced more ECM than heifers that were a lesser proportion (Figure 4.2). The relationship between pctLWT21 and ECM for FJ heifers was predominantly curvilinear, with greater milk production responses at lower pctLWT21 compared with greater pctLWT21 (Figure 4.2). Similar relationships were found for breed groups other than FJ (Appendix III). Due to lower numbers of records at the extremes for pctLWT21, results are presented for heifers that were between 40 and 70% of 21-month LWT at 12 months of age (Figure 4.2).

Table 4.3 Number of records (N) and least-squares means ± SEM of first lactation energy-corrected milk (ECM) and milksolids yield for heifers that were tiny, small, average, big or huge at 21 months of age within each breed group[1].

Breed group and LWT category		N	ECM (L)	Milksolids (kg)
F				
	Tiny	6,475	3,694.3^{a} ± 20.8	281.5^{a} ± 1.6
	Small	6,880	3,893.1^{b} ± 20.6	295.9^{b} ± 1.6
	Average	6,897	4,029.5^{c} ± 20.6	305.9^{c} ± 1.6
	Big	7,112	4,134.5^{d} ± 20.6	313.6^{d} ± 1.6
	Huge	7,572	4,334.2^{e} ± 20.9	328.3^{e} ± 1.6
FX				
	Tiny	8,847	3,680.8^{a} ± 20.2	282.1^{a} ± 1.5
	Small	9,186	3,903.3^{b} ± 20.0	298.6^{b} ± 1.5
	Average	9,253	4,025.2^{c} ± 20.0	307.7^{c} ± 1.5
	Big	9,413	4,130.7^{d} ± 20.0	315.5^{d} ± 1.5
	Huge	9,991	4,317.4^{e} ± 20.1	329.4^{e} ± 1.5
FJ				
	Tiny	5,949	3,653.8^{a} ± 20.9	281.2^{a} ± 1.6
	Small	6,154	3,853.9^{b} ± 20.7	296.3^{b} ± 1.6
	Average	6,209	3,979.1^{c} ± 20.7	305.6^{c} ± 1.6
	Big	6,411	4,082.2^{d} ± 20.6	313.4^{d} ± 1.6
	Huge	6,650	4,258.9^{e} ± 20.7	326.4^{e} ± 1.6
JX				
	Tiny	3,463	3,580.1^{a} ± 22.5	276.6^{a} ± 1.7
	Small	3,485	3,777.9^{b} ± 22.2	291.5^{b} ± 1.7
	Average	3,498	3,881.2^{c} ± 22.2	299.2^{c} ± 1.7
	Big	3,449	3,978.6^{d} ± 22.2	306.3^{d} ± 1.7
	Huge	3,500	4,160.7^{e} ± 22.3	319.8^{e} ± 1.7
J				
	Tiny	2,009	3,306.4^{a} ± 28.5	256.3^{a} ± 2.2
	Small	2,001	3,508.2^{b} ± 27.2	272.1^{b} ± 2.1
	Average	1,966	3,648.8^{c} ± 26.9	282.8^{c} ± 2.1
	Big	1,898	3,785.2^{d} ± 27.0	293.4^{d} ± 2.1
	Huge	1,845	3,922.6^{e} ± 27.7	303.5^{e} ± 2.1

[a-d] Values within a breed group and LWT category with different superscripts differ at $P<0.01$.

[1]F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

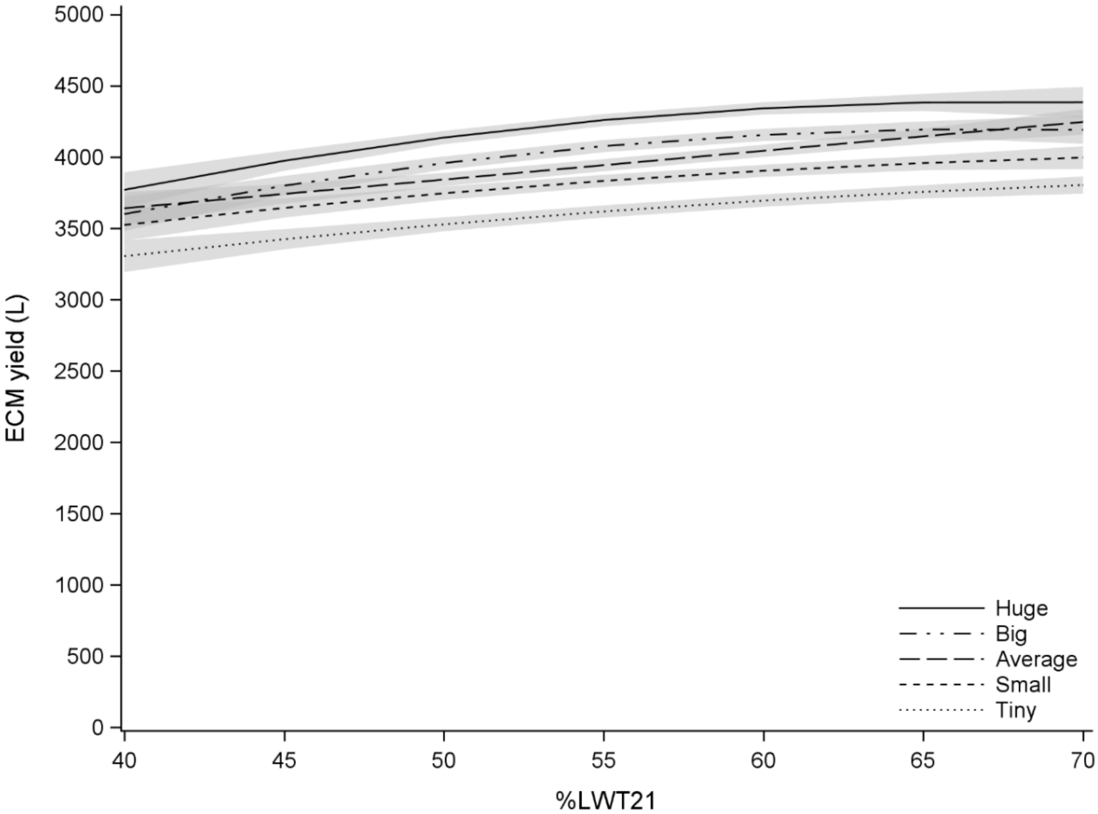

Figure 4.2 Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and first lactation energy-corrected milk (ECM) production for Holstein-Friesian-Jersey crossbred (FJ) heifers that were tiny, small, average, big or huge at 21 months of age. Shaded area indicates 95% confidence intervals.

Based on the 95% confidence intervals, heifers that were 65% of their 21-month LWT produced greater ECM and milksolids yields compared with heifers that were 45% of their 21-month LWT for all breed groups and LWT categories (Table 4.4 and Table 4.5). For F, FX and FJ heifers of all LWT categories, heifers that were 55% of their 21-month LWT at 12 months of age produced more ECM and milksolids than those that were 45%, likewise, those that were 65% produced more than those that were 55% (Table 4.4 and Table 4.5). For FJ heifers that were average at 21 months of age, those that were 45% of pctLWT21 produced 3,741.3 L of ECM, less than those that were 55% of pctLWT21 (3,942.8 L), and less than those that were 65% of pctLWT21 (4,144.9 L). A similar relationship was found for JX heifers that were tiny, small, average or big, and J heifers that were huge (Table 4.4 and Table 4.5).

There were no differences in first lactation ECM or milksolids between JX heifers that were 55% or 65% of pctLWT21 that were huge at 21 months of age (4,168 and 4,261.3 L ECM and 320.3 and 328.1 kg milksolids, respectively). However, huge JX heifers that were 55% or 65% produced greater quantities of ECM and milksolids compared with huge JX heifers that were 45% of their 21-month LWT (3,887.8 L ECM and 298.5 kg milksolids).

Jersey heifers that grew to 55% or 65% of pctLWT21 produced similarly, but more than those that were 45% of pctLWT21 if they were tiny, average or big at 21 months of age (Table 4.4 and Table 4.5). Small J heifers that were 45% of pctLWT21 produced similar quantities of ECM and milksolids to heifers that were 55%, but less than heifers that were 65% (Table 4.4 and Table 4.5).

Table 4.4 Predicted first lactation energy-corrected milk (ECM) yield (±SEM) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		ECM (L)		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	3,534.8^{a} ± 33.2	3,666.9^{b} ± 21.1	3,779.6^{c} ± 23.4
	Small	3,643.1^{a} ± 36.3	3,866.5^{b} ± 21.1	4,038.2^{c} ± 25.0
	Average	3,800.8^{a} ± 39.2	4,008.0^{b} ± 21.2	4,169.5^{c} ± 26.0
	Big	3,900.4^{a} ± 39.9	4,105.3^{b} ± 21.2	4,316.6^{c} ± 26.7
	Huge	4,078.6^{a} ± 37.0	4,335.1^{b} ± 21.4	4,479.9^{c} ± 28.3
FX				
	Tiny	3,523.8^{a} ± 30.4	3,657.3^{b} ± 20.5	3,754.3^{c} ± 22.1
	Small	3,723.7^{a} ± 31.7	3,869.7^{b} ± 20.4	4,033.3^{c} ± 23.4
	Average	3,787.2^{a} ± 31.5	4,000.4^{b} ± 20.4	4,167.2^{c} ± 24.5
	Big	3,879.1^{a} ± 33.2	4,104.0^{b} ± 20.4	4,300.1^{c} ± 25.5
	Huge	3,983.7^{a} ± 34.2	4,314.1^{b} ± 20.4	4,461.6^{c} ± 26.3
FJ				
	Tiny	3,423.4^{a} ± 35.8	3,618.3^{b} ± 21.5	3,756.0^{c} ± 23.4
	Small	3,643.0^{a} ± 34.2	3,832.9^{b} ± 21.5	3,957.8^{c} ± 25.5
	Average	3,741.3^{a} ± 34.3	3,942.8^{b} ± 21.4	4,144.9^{c} ± 27.0
	Big	3,799.1^{a} ± 34.6	4,076.7^{b} ± 21.4	4,193.5^{c} ± 28.5
	Huge	3,973.6^{a} ± 35.5	4,259.3^{b} ± 21.3	4,383.1^{c} ± 30.4
JX				
	Tiny	3,380.2^{a} ± 47.4	3,557.5^{b} ± 23.7	3,657.1^{c} ± 25.7
	Small	3,580.7^{a} ± 42.1	3,756.2^{b} ± 23.6	3,884.0^{c} ± 29.3
	Average	3,658.0^{a} ± 39.5	3,863.4^{b} ± 23.7	4,007.8^{c} ± 32.1
	Big	3,704.1^{a} ± 37.9	3,970.4^{b} ± 23.5	4,130.1^{c} ± 34.4
	Huge	3,887.8^{a} ± 38.7	4,168.0^{b} ± 23.5	4,261.3^{b} ± 38.5
J				
	Tiny	2,993.9^{a} ± 78.7	3,305.4^{b} ± 31.8	3,387.7^{b} ± 33.2
	Small	3,359.0^{a} ± 64.1	3,502.8^{ab} ± 29.9	3,598.7^{b} ± 35.2
	Average	3,368.4^{a} ± 65.7	3,660.7^{b} ± 29.5	3,742.3^{b} ± 37.9
	Big	3,501.2^{a} ± 52.4	3,806.0^{b} ± 29.7	3,877.1^{b} ± 42.8
	Huge	3,625.8^{a} ± 41.9	3,942.3^{b} ± 29.8	4,131.0^{c} ± 53.1

$^{a-c}$ Values within a row with different superscripts differ at the 95% confidence interval.

F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Table 4.5 Predicted first lactation milksolids yield (±SEM) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		Milksolids (kg)		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	$269.7^{a} \pm 2.6$	$279.4^{b} \pm 1.6$	$287.8^{c} \pm 1.8$
	Small	$276.7^{a} \pm 2.8$	$293.8^{b} \pm 1.6$	$307.1^{c} \pm 1.9$
	Average	$288.0^{a} \pm 3.0$	$304.2^{b} \pm 1.6$	$316.7^{c} \pm 2.0$
	Big	$295.5^{a} \pm 3.1$	$311.4^{b} \pm 1.6$	$327.8^{c} \pm 2.0$
	Huge	$308.1^{a} \pm 2.8$	$328.3^{b} \pm 1.6$	$339.9^{c} \pm 2.2$
FX				
	Tiny	$270.1^{a} \pm 2.3$	$280.2^{b} \pm 1.6$	$287.7^{c} \pm 1.7$
	Small	$284.5^{a} \pm 2.4$	$296.0^{b} \pm 1.6$	$308.7^{c} \pm 1.8$
	Average	$289.2^{a} \pm 2.4$	$305.7^{b} \pm 1.6$	$318.9^{c} \pm 1.9$
	Big	$295.7^{a} \pm 2.5$	$313.3^{b} \pm 1.6$	$328.9^{c} \pm 2.0$
	Huge	$303.3^{a} \pm 2.6$	$329.0^{b} \pm 1.6$	$341.0^{c} \pm 2.0$
FJ				
	Tiny	$263.3^{a} \pm 2.8$	$278.4^{b} \pm 1.7$	$289.1^{c} \pm 1.8$
	Small	$279.8^{a} \pm 2.6$	$294.7^{b} \pm 1.6$	$304.5^{c} \pm 2.0$
	Average	$286.9^{a} \pm 2.6$	$302.8^{b} \pm 1.6$	$318.6^{c} \pm 2.1$
	Big	$290.9^{a} \pm 2.7$	$312.9^{b} \pm 1.6$	$322.3^{c} \pm 2.2$
	Huge	$304.1^{a} \pm 2.7$	$326.4^{b} \pm 1.6$	$336.4^{c} \pm 2.3$
JX				
	Tiny	$260.7^{a} \pm 3.6$	$274.8^{b} \pm 1.8$	$282.7^{c} \pm 2.0$
	Small	$275.6^{a} \pm 3.2$	$289.8^{b} \pm 1.8$	$300.0^{c} \pm 2.3$
	Average	$281.5^{a} \pm 3.0$	$297.8^{b} \pm 1.8$	$309.1^{c} \pm 2.5$
	Big	$284.7^{a} \pm 2.9$	$305.7^{b} \pm 1.8$	$318.0^{c} \pm 2.6$
	Huge	$298.5^{a} \pm 3.0$	$320.3^{b} \pm 1.8$	$328.1^{b} \pm 3.0$
J				
	Tiny	$231.6^{a} \pm 6.1$	$256.2^{b} \pm 2.4$	$262.8^{b} \pm 2.5$
	Small	$260.0^{a} \pm 4.9$	$271.6^{ab} \pm 2.3$	$279.3^{b} \pm 2.7$
	Average	$260.4^{a} \pm 5.1$	$283.8^{b} \pm 2.3$	$290.2^{b} \pm 2.9$
	Big	$271.0^{a} \pm 4.0$	$295.0^{b} \pm 2.3$	$300.8^{b} \pm 3.3$
	Huge	$280.1^{a} \pm 3.2$	$304.9^{b} \pm 2.3$	$320.2^{c} \pm 4.1$

$^{a-c}$ Values within a row with different superscripts differ at the 95% confidence interval.
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

4.4.3 Three-parity milk production

Similar to first lactation, F, FX and FJ heifers that were smaller at 21 months of age produced less (P<0.001) three-parity ECM and milksolids than heifers of the same breed group that were larger (Table 4.6). For example, tiny FJ heifers produced 9,702.8 kg of ECM, 7% less than that of small FJ heifers and 10%, 13% and 16% less than that of average, big and huge FJ heifers, respectively. Average and big JX heifers produced similar (P>0.05) quantities of ECM and milksolids, but more (P<0.01) than small JX heifers. Likewise, big and huge J heifers also produced similar (P>0.05) quantities of ECM and milksolids, but more (P<0.01) than average J heifers (Table 4.6).

Heifers that were a greater proportion of their 21-month LWT at 12 months of age produced more three-parity ECM than heifers that were a lesser proportion of their 21-month LWT, within LWT category and breed group (Figure 4.3). The relationship between pctLWT21 and ECM was predominantly curvilinear, with greater milk production responses at lower pctLWT21 compared with greater pctLWT21 (Figure 4.3). Due to lower number of records at the extremes for pctLWT21, results are presented for FJ heifers that were between 40 and 70% of 21-month LWT at 12 months of age (Figure 4.3).

Table 4.6 Number of records (N) and least-squares means ± SEM of three-parity energy-corrected milk (ECM) and milksolids yield for heifers that were tiny, small, average, big or huge at 21 months of age within each breed group[1].

Breed group and LWT category	N	ECM (L)	Milksolids (kg)
F			
Tiny	3,086	9,450.6^{a} ± 124.8	720.0^{a} ± 9.6
Small	3,316	10,117.0^{b} ± 121.2	767.7^{b} ± 9.3
Average	3,310	10,587.0^{c} ± 121.4	803.2^{c} ± 9.3
Big	3,310	10,908.0^{d} ± 122.3	826.7^{d} ± 9.4
Huge	3,360	11,192.0^{e} ± 126.8	847.1^{e} ± 9.7
FX			
Tiny	4,271	9,702.8^{a} ± 115.9	744.1^{a} ± 8.9
Small	4,352	10,466.0^{b} ± 113.9	800.6^{b} ± 8.8
Average	4,577	10,768.0^{c} ± 113.0	823.1^{c} ± 8.7
Big	4,491	11,096.0^{d} ± 114.0	847.3^{d} ± 8.8
Huge	4,501	11,495.0^{e} ± 115.8	876.7^{e} ± 8.9
FJ			
Tiny	2,993	9,653.8^{a} ± 124.7	744.0^{a} ± 9.6
Small	2,870	10,286.0^{b} ± 124.1	791.9^{b} ± 9.5
Average	3,031	10,768.0^{c} ± 122.6	828.0^{c} ± 9.4
Big	3,172	11,106.0^{d} ± 121.9	853.3^{d} ± 9.4
Huge	3,088	11,438.0^{e} ± 123.5	877.5^{e} ± 9.5
JX			
Tiny	1,792	9,197.2^{a} ± 142.5	712.3^{a} ± 11.0
Small	1,707	10,038.0^{b} ± 141.4	775.9^{b} ± 10.9
Average	1,696	10,573.0^{c} ± 141.2	816.5^{cd} ± 10.9
Big	1,744	10,583.0^{c} ± 140.3	816.2^{c} ± 10.8
Huge	1,733	10,900.0^{d} ± 141.6	838.8^{d} ± 10.9
J			
Tiny	1,230	8,111.3^{a} ± 198.1	630.5^{a} ± 15.2
Small	1,137	9,010.5^{b} ± 186.5	700.7^{b} ± 14.3
Average	1,151	9,472.5^{c} ± 182.7	736.6^{c} ± 14.1
Big	1,028	9,910.0^{d} ± 186.7	770.0^{d} ± 14.4
Huge	887	10,254.0^{d} ± 197.7	794.4^{d} ± 15.2

[a-e] Values within a breed group and LWT category with different superscripts differ at P<0.01.

[1]F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

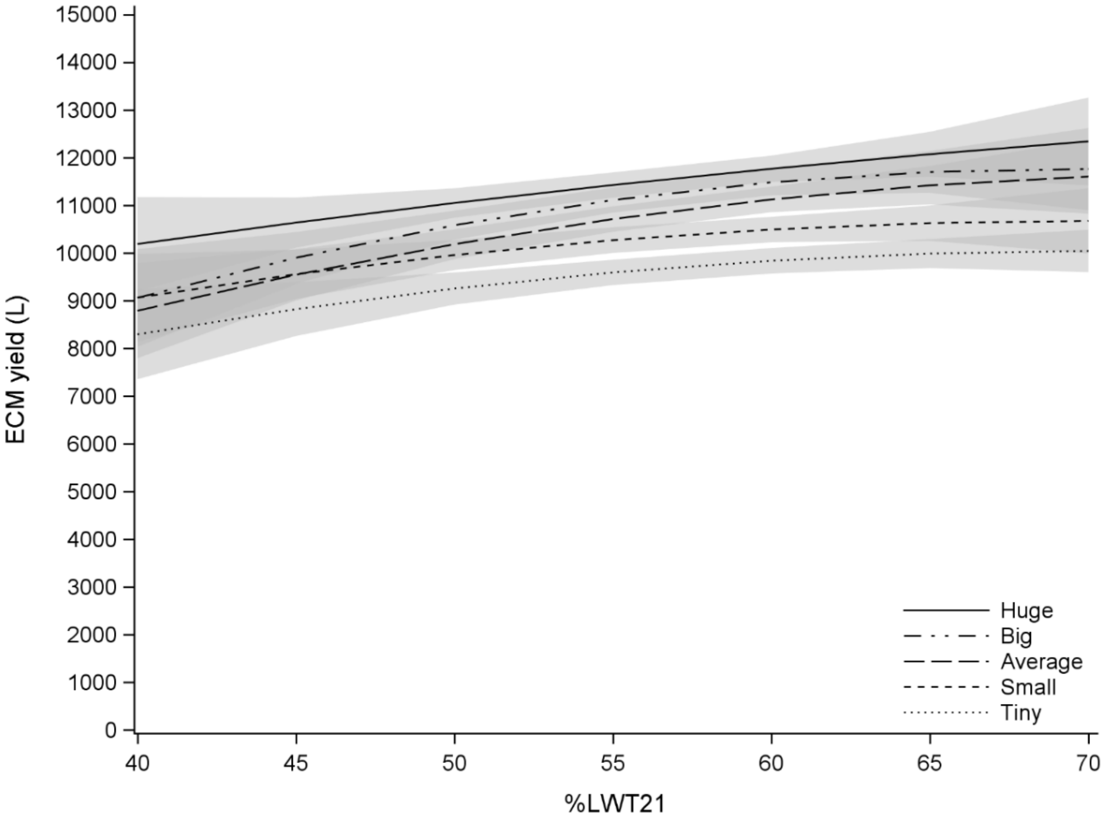

Figure 4.3 Relationship between proportion of 21-month live weight at 12 months of age (pctLWT21) and three-parity energy-corrected milk (ECM) production for Holstein-Friesian-Jersey crossbred (FJ) heifers that were tiny, small, average, big or huge at 21 months of age. Shaded area indicates 95% confidence intervals.

Holstein-Friesian, FX and FJ heifers that were 65% of their 21-month LWT at 12 months of age produced greater three-parity ECM and milksolids yields compared with heifers of the same breed group that were 45% of their 21-month LWT (Table 4.7 and Table 4.8). The numerical difference was greater between heifers that were 55% and 45% than the difference between heifers that were 65% and 55% (Table 4.7 and Table 4.8). For example, the difference between 45% and 55% FJ heifers that were of average size at 21 months of age was 1,167.5 L of ECM, whereas the difference between 55% and 65% was 707 L of ECM; further emphasizing the curvilinear relationship between pctLWT21 and milk production.

Jersey crossbred heifers that were tiny or small at 21 months of age produced similar quantities of three-parity ECM or milksolids if they were 45%, 55% or 65% of their 21-month LWT at 12 months of age (Table 4.7 and Table 4.8). For JX heifers that were average, big or huge at 21 months of age, being a greater pctLWT21 at 12 months of age positively impacted three-parity ECM and milksolids yields (Table 4.7 and Table 4.8).

For J heifers, being a greater pctLWT21 at 12 months of age had no impact on three-parity ECM or milksolids production for heifers that were small, average, big or huge at 21 months of age. However, if the J heifers were tiny at 21 months of age, the heifers that were closer to their 21-month LWT (65% or 55%) produced more ECM and milksolids than the heifers that were further away from their 21-month LWT (45%) at 12 months of age (Table 4.7 and Table 4.8).

Table 4.7 Predicted three-parity energy-corrected milk (ECM) yield (±SEM) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category	ECM (L)		
	45% LWT21	55% LWT21	65% LWT21
F			
Tiny	8,115.3^{a} ± 268.2	9,491.6^{b} ± 130.3	9,876.7^{b} ± 164.6
Small	8,429.8^{a} ± 284.2	10,091.0^{b} ± 131.0	10,898.0^{c} ± 186.1
Average	9,197.9^{a} ± 310.1	10,556.0^{b} ± 130.8	11,294.0^{c} ± 188.8
Big	9,561.6^{a} ± 326.2	10,843.0^{b} ± 132.7	11,759.0^{c} ± 193.4
Huge	10,425.0^{a} ± 310.6	11,285.0^{ab} ± 136.8	11,690.0^{b} ± 208.4
FX			
Tiny	9,147.0^{a} ± 242.5	9,668.3^{ab} ± 121.4	9,953.8^{b} ± 142.7
Small	9,391.0^{a} ± 252.1	10,460.0^{b} ± 120.7	10,899.0^{b} ± 160.9
Average	9,937.4^{a} ± 249.1	10,739.0^{b} ± 119.8	11,243.0^{b} ± 171.1
Big	10,131.0^{a} ± 256.1	10,996.0^{b} ± 121.1	11,976.0^{c} ± 187.5
Huge	10,233.0^{a} ± 265.1	11,588.0^{b} ± 122.6	11,920.0^{b} ± 194.6
FJ			
Tiny	8,822.4^{a} ± 285.8	9,594.0^{ab} ± 134.5	9,988.4^{b} ± 153.8
Small	9,555.7^{a} ± 261.1	10,270.0^{ab} ± 136.0	10,628.0^{b} ± 188.0
Average	9,545.5^{a} ± 273.1	10,713.0^{b} ± 133.8	11,420.0^{c} ± 203.6
Big	9,900.5^{a} ± 273.8	11,112.0^{ab} ± 132.3	11,700.0^{b} ± 222.4
Huge	10,638.0^{a} ± 266.7	11,426.0^{b} ± 133.8	12,072.0^{b} ± 238.7
JX			
Tiny	8,533.2 ± 363.2	9,184.4 ± 154.6	9,439.9 ± 179.2
Small	9,564.7 ± 334.1	10,001.0 ± 160.0	10,361.0 ± 234.4
Average	9,526.3^{a} ± 302.5	10,580.0^{b} ± 159.7	11,073.0^{b} ± 253.7
Big	9,177.2^{a} ± 278.7	10,576.0^{b} ± 155.0	11,505.0^{c} ± 286.2
Huge	10,061.0^{a} ± 285.8	10,911.0^{ab} ± 156.1	11,481.0^{b} ± 317.2
J			
Tiny	6,323.4^{a} ± 580.4	7,998.6^{b} ± 225.2	8,620.5^{b} ± 246.9
Small	8,000.9 ± 494.5	8,985.9 ± 212.6	9,496.1 ± 278.8
Average	8,675.0 ± 506.5	9,519.6 ± 207.5	9,837.1 ± 292.7
Big	9,284.5 ± 436.5	10,117.0 ± 213.7	9,885.1 ± 334.0
Huge	9,359.6 ± 343.8	10,430.0 ± 226.3	10,698.0 ± 436.4

$^{a-c}$ Values within a row with different superscripts differ at the 95% confidence interval.
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Table 4.8 Predicted three-parity milksolids yield (±SEM) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		Milksolids (kg)		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	619.5^{a} ± 20.6	723.2^{b} ± 10.0	751.8^{b} ± 12.7
	Small	639.3^{a} ± 21.9	765.8^{b} ± 10.1	826.7^{c} ± 14.3
	Average	696.6^{a} ± 23.9	801.0^{b} ± 10.1	857.2^{c} ± 14.5
	Big	722.7^{a} ± 25.1	821.7^{b} ± 10.2	892.2^{c} ± 14.9
	Huge	786.0^{a} ± 23.9	854.1^{b} ± 10.5	886.3^{b} ± 16.0
FX				
	Tiny	701.5^{a} ± 18.7	741.4^{ab} ± 9.3	763.4^{b} ± 11.0
	Small	718.3^{a} ± 19.4	800.1^{b} ± 9.3	834.1^{b} ± 12.4
	Average	759.3^{a} ± 19.2	820.8^{b} ± 9.2	860.1^{b} ± 13.2
	Big	773.0^{a} ± 19.7	839.5^{b} ± 9.3	915.5^{c} ± 14.4
	Huge	778.9^{a} ± 20.4	883.6^{b} ± 9.4	910.9^{b} ± 15.0
FJ				
	Tiny	679.1^{a} ± 22.0	739.4^{ab} ± 10.3	770.1^{b} ± 11.8
	Small	735.1^{a} ± 20.1	790.7^{ab} ± 10.5	818.6^{b} ± 14.5
	Average	733.6^{a} ± 21.0	823.7^{b} ± 10.3	878.3^{c} ± 15.7
	Big	759.7^{a} ± 21.1	853.5^{ab} ± 10.2	900.5^{b} ± 17.1
	Huge	815.3^{a} ± 20.5	876.6^{b} ± 10.3	926.6^{b} ± 18.4
JX				
	Tiny	661.1 ± 27.9	711.3 ± 11.9	731.0 ± 13.8
	Small	736.9 ± 25.7	773.3 ± 12.3	801.2 ± 18.0
	Average	734.8^{a} ± 23.3	817.2^{b} ± 12.3	855.3^{b} ± 19.5
	Big	707.0^{a} ± 21.4	815.5^{b} ± 11.9	888.1^{c} ± 22.0
	Huge	775.0^{a} ± 22.0	839.4^{ab} ± 12.0	884.3^{b} ± 24.4
J				
	Tiny	491.2^{a} ± 44.6	621.9^{b} ± 17.3	670.1^{b} ± 19.0
	Small	622.5 ± 38.0	698.9 ± 16.4	738.3 ± 21.4
	Average	673.4 ± 39.0	740.4 ± 16.0	765.1 ± 22.5
	Big	720.7 ± 33.6	786.1 ± 16.4	768.4 ± 25.7
	Huge	724.5 ± 26.4	807.8 ± 17.4	830.4 ± 33.6

$^{a\text{-}c}$ Values within a row with different superscripts differ at the 95% confidence interval.
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

4.5 Discussion

Heifers that had reached a higher percentage of their 21-month LWT at 12 months of age grew faster in their first year of life and produced more milk in first lactation than heifers that were further from their 21-month LWT at 12 months of age, regardless of how heavy the heifer was at 21 months of age. This indicates that increased growth in early life may be beneficial to future milk production.

Previous studies have reported that heifers that were heavier in the months before first calving (21-24 months of age) produced greater quantities of milk in first and subsequent lactations compared with heifers that were lighter (McNaughton & Lopdell 2013; van der Waaij et al. 1997). The current study supported these results; heifers that were categorised as tiny for their breed group at 21 months of age produced less milk in first and three-parity lactation than heifers that were small, and likewise for the larger LWT categories for all five breed groups.

Additionally, this study demonstrated that the growth pattern in which the 21-month LWT was attained did influence milk production. Heifers that did a large proportion of growing in their first year (up to 12 months of age), and hence were a greater pctLWT21 produced more milk in first and three-parity lactation than heifers that did a small proportion of their growing in their first year. The heifers that were a lesser pctLWT21 did a larger proportion of their growing in their second year (12 to 21 months of age) compared with their first year. Lacasse et al. (1993) reported that milk production was not affected by plane of nutrition during the second year of rearing. A high plane of nutrition (ad libitum vs moderate feeding from one-year-old to the third month of gestation) did not increase milk production during first lactation (Lacasse et al. 1993). The results from the current study and those from Lacasse et al. (1993) indicate the importance of good early life growth compared with later-in-life growth.

As mentioned earlier, one of the periods of slowest growth of heifers occurred between five and 12 months of age (Chapter 2), which in New Zealand, coincides with a seasonal variation in pasture quality and quantity, resulting in heifers being the furthest from target LWT when they were 12 months of age (Handcock et al. 2016). Previous research has indicated that heifers may benefit from increased pasture allowances or supplementary feeding to improve growth rates leading up to 12 months of age (Chapter 3). The results from the current study also support this suggestion; that growth up to 12 months of age is important for milk production, independent of LWT at

21 months of age. Chester-Jones et al. (2017) and Soberon et al. (2012) reported that LWT at pre-weaning and weaning, and LWT gain post-weaning had positive effects on first-lactation and accumulated milk yields. The current study extends from the results of Chester-Jones et al. (2017) and Soberon et al. (2012), and identifies that growth up to 12 months of age is also important for milk production.

The age at which puberty is attained is approximately 12 months of age, dependent on breed and growth rates (Hickson et al. 2011; Macdonald et al. 2007). Rapid growth during the pre-pubertal allometric phase of mammary development can give rise to excessive fat deposition in the mammary gland; termed “Fatty Udder Syndrome” (Moran 1996). However, there is conflicting evidence that rapid growth rates during this period will affect subsequent milk production (Capuco et al. 1995; Dobos et al. 2000; Macdonald et al. 2005; Penno 1997). Heifers in the current study that were closer to their 21-month LWT at 12 months of age (heavier) produced more milk than those further away (lighter). To be heavier at 12 months of age, they had to have grown faster, therefore, the heifers that grew faster up to 12 months of age produced more than those that grew slower. These results are contradictory to reports of Fatty Udder Syndrome, however, the majority of studies that reported incidence of impaired mammary development due to increased growth rates were based in total mixed ration (TMR) systems (Sejrsen 1994). Addition of higher proportions of protein in the diet were found to reduce the incidence of increased fat deposition in the udder (Capuco et al. 1995). Therefore, in pasture-based systems, such as those found in New Zealand where energy is the first limiting factor in the diet, “fatty udder syndrome” is unlikely to be an issue for faster growing heifers. It appears that the underfeeding of heifers is likely to be a greater issue in terms of milk production potential compared with overfeeding.

There are few studies that have analysed milk production accumulated over multiple lactations (Archer et al. 2013; Bettenay 1985; Heinrichs & Heinrichs 2011; Lin et al. 1988; Soberon et al. 2012). Of these studies there were only two that examined relationships between LWT and accumulated milk production over multiple lactations (Bettenay 1985; Heinrichs & Heinrichs 2011), neither of which studied growth rate or growth pattern effects. As mentioned in Chapter 3, the study by Heinrichs and Heinrichs (2011) concluded there was no effect of LWT at first calving on accumulated milk yield, and did not study the effects of earlier LWTs. Bettenay (1985) had a small sample size of 18 heifers per treatment when comparing four ages and two LWTs at mating. After mating, heifers were run together, allowing the smaller heifers to grow faster and catch up to the larger heifers (Bettenay 1985). Additionally, only heifers that completed four lactations were used to estimate accumulated yield over four lactations. Analysing the relationship including only the survivors does not truly describe the impact of light heifers on milk production, as it does not take into account how long the heifers actually remained productive for, in addition to the decreased milk production (Archer et al. 2013). Therefore, the data in the current study for three-parity production includes all heifers that were old enough to have completed three lactations, regardless of whether they did or not.

Based on their first lactation production and results from previous studies (Lembeye et al. 2016; Macdonald et al. 2005), the mean three-parity yields for the breed groups is less than what would be expected if only cows that had completed all three lactations were included. This reflects that approximately 34% of the 67,833 heifers in the current study for three-parity yields failed to complete all three lactations. The costs of rearing a heifer are incurred regardless of how long she remains in the herd and is producing. Including the heifers that did not complete all three lactations describes the effect that growth of replacement heifers has on accumulated milk yields without discriminating whether the increased milk yield came from greater survival or from greater production per surviving cow.

The relationship between pctLWT21 and three-parity milk yields was less pronounced than the relationship between pctLWT21 and first lactation milk yields. A contributing factor to this may be the greater variation in three-parity milk yields compared with first lactation milk yields (CV of 43% vs 28% for three-parity and first lactation ECM yields, respectively) for the datasets used. One reason may be that the heifers that grew more in their first year in the current study may have survived to complete two or three lactations and hence their three-parity milk yields were much greater than the heifers that were a lesser pctLWT21 may have only survived to complete one or two lactations. Further research on the relationships between pctLWT21 and survival of heifers is required to confirm this but could explain why the relationship between pctLWT21 and three-parity milk yields was less pronounced than the relationship between pctLWT21 and first lactation milk production.

4.6 Conclusion

Plane of nutrition in the first year of a heifer's life is important for future milk production. Heifers that were grown to be closer to their 21-month LWT at 12 months of age produced more milk than heifers that were further from their 21-month LWT at 12 months of age. The effect of being a greater pctLWT21 was more pronounced in first lactation milk yields compared with three-parity milk yields.

Foreword to Chapters 5 and 6

Results from Chapters 3 and 4 included the effects of LWT at three-monthly increments from three to 21 months of age on milk production. In the seasonal pasture-based system, heifers are generally mated for the first time at approximately 15 months of age in order to calve at 24 months of age and maintain the 365-day calving interval required in the herd. Therefore, LWTs beyond 15 months of age cannot be used as an estimator for first mating performance as the event had already occurred (i.e. the heifer would already be pregnant or not pregnant by this time). Chapters 5 and 6 will include results of LWT effects on stayability and calving rates, which is an outcome of first mating performance. Therefore, LWTs at 18 and 21 months of age are not considered in Chapters 5 and 6 for this reason even though they were analysed in Chapters 3 and 4.

To keep the chapters concise, only three ages for LWT effects on stayability and reproduction have been included; six months of age, 12 months of age and 15 months of age. The main reasons for including these ages are outlined below:

- Six months of age due to the current industry target LWT of 30% mature LWT.
- Twelve months of age due to this occurring during the period of slowest growth of heifers (Chapter 2), and it ties in with 12-month LWT as a proportion of 21-month LWT that was reported in Chapter 4 and will be reported in Chapters 5 and 6. Twelve months of age is also the period where farmers/graziers have approximately three months to assess and improve heifer performance leading into mating. In addition, there is often an increase in feed supply, thus extra feed can be provided for heifers if they require it.
- Fifteen months of age due to the current industry target of 60% mature LWT. In addition, a large number of studies model LWT at 15 months of age to estimate reproductive performance as this is a common age of first mating.

Chapter 5 Stayability of dairy heifers as affected by live weight and growth prior to first calving

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5.1 Abstract

This study investigated the relationships between live weight (LWT) and stayability of 189,936 New Zealand dairy heifers. Heifers were classified into five breed groups; Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Jersey (J), Jersey crossbred (JX) and Holstein-Friesian-Jersey crossbred (FJ). Live weights were assessed at six, 12 and 15 months of age and their relationships with stayability over the first three calvings were analysed. In addition, the relationships between proportion of LWT achieved at 12 months of age with respect to LWT at 21 months of age (pctLWT21) and stayability were analysed to estimate the effect of increased growth in the first year of life on stayability. Approximately 92% of heifers that were reared, calved for the first time as two-year-olds, 76% a second time as three-year-olds and 61% a third time as four-year-olds. Heifers that were heavier were more likely to remain in the herd for first, second and third calving compared with heifers that were lighter. Furthermore, plane of nutrition in the first year of a heifer's life was important for stayability to first, second and third calvings. Heifers that were moderately well-grown at 12 months of age relative to their 21-month LWT were more likely to remain in the herd compared with heifers that were further from their 21-month LWT at 12 months of age. For heifers that were at the heaviest end of the LWT range in the current study, there was a slight decline in stayability compared with heifers in the mid-range of LWT. Consequently, for heifers that were above average in LWT the benefit of increasing LWT before first mating would be small and may even result in a slight decline in stayability. However, for heifers that were below average in LWT, considerable benefits to stayability are predicted by improving rearing practices to result in heavier heifers throughout the premating rearing phase.

5.2 Introduction

Herds that have greater cow survival rates will have a greater proportion of mature, high producing cows and a lower proportion of replacement heifers needing to be reared compared with herds that have low cow survival rates (Pritchard et al. 2013). Recording fates of dairy cows in the New Zealand system is voluntary, and large proportions of cows have missing dates and/or reasons for removal (43%; n=6,988,011 out of 16,399,396 considered (Kerslake et al. 2018)). A measure of cow survival that does not require recording of cull data is stayability (STAY); Hudson and Van Vleck (1981) defined STAY as the probability of an animal surviving to a specific age given that they had the opportunity to reach that age. Most studies have the first calving event as the base level (Brickell & Wathes 2011), and express STAY as a binary trait indicating presence or absence at later calving events. A second measure of survival is marginal stayability (MSTAY); it is expressed as the probability of being present at the subsequent calving (n +1), given an animal's presence at a particular calving (n) (McIntyre et al. 2012).

Pritchard et al. (2013) and Brickell et al. (2009b) reported that 13.7% and 14.5%, respectively, of Holstein-Friesian heifers in the United Kingdom did not survive to first calving. Meier et al. (2017) reported that the loss of Holstein-Friesian heifers from collection (approx. nine days of age) to 17 months of age for a New Zealand research herd on divergent genetic fertility was 4.8% and 9.8%, for heifers that were of high (n=289) or low (n=276) genetic merit for fertility, respectively. Further results from these same heifers have been reported by Burke et al. (2018), and the final non-pregnancy rate after the first mating period of 14 weeks was 2% for the high and 6% for the low fertility heifers. Burke et al. (2018) did not report the number of heifers from which the non-pregnancy rate was calculated, but if the final number remaining at 17 months of age reported by Meier et al. (2017) is assumed, this equates to approximately 7% of the high and 15% of the low fertility heifers failed to remain in the herd until first calving (Burke et al. 2018; Meier et al. 2017). Reasons for removal included poor conformation, freemartinism, poor health and death (Meier et al. 2017). Reasons for lack of survival from the United Kingdom studies were not known, the authors postulated it might be due to illness, trauma or reproductive failure (Pritchard et al. 2013).

The heritability of heifer survival was low (0.01), suggesting that environmental factors influenced heifers' survival to 25 months of age to a greater extent than genetics (Pritchard et al. 2013). A suggestion to improve heifers' survival was to improve the management of heifers (Pritchard et al. 2013), which may result in an improvement in heifer live weight (LWT). More of the heavier Holstein-Friesian heifers were present at the beginning of first (93% vs 82%) and second (76% vs 62%) lactation compared with the lighter heifers (Archbold et al. 2012); emphasizing the survival benefits of having Holstein-Friesian heifers heavier at mating. In addition, the data from Pritchard et al. (2013), Brickell et al. (2009b) and Archbold et al. (2012) indicated that survival studies that use first calving as the baseline may not capture the wastage that occurs when heifers don't survive to first calving (Brickell & Wathes 2011).

McNaughton and Lopdell (2013) reported that heifers that did not have any calving dates recorded were a lower percentage of target LWT (between 15 and 17 months of age) compared with heifers that did have a recorded calving date. Likewise, heifers that had only one calving date recorded were a lower percentage of target LWT compared with heifers that had two calving dates recorded (McNaughton & Lopdell 2013). McNaughton and Lopdell (2013) did not report differences among breeds in probability of calving each year as related to target LWT.

Bach (2011) reported that Holstein heifers that reached second lactation grew more (0.8 kg/d) between 12 and 65 days of age than heifers that did not reach second lactation (0.7 kg/d). Bach (2011) also reported that the effect of average daily gain (ADG) from 12 days of age to first breeding on survivability to second lactation approached significance, but there was no effect of growth rate after breeding on survivability. In addition, growth rate between 100 and 200 kg or 200 kg and 22 months of age for Holstein-Friesian or between 80 and 165 kg or 165 kg and 22 months of age for Jersey heifers had no impact on first calving date, or proportion of heifers surviving to second or third lactation (Macdonald et al. 2005). However, there were differences in proportion of heifers cycling prior to first mating in the study by Macdonald et al. (2005) in that a lower proportion of heifers that grew slower were cycling compared with heifers that grew faster. Oestrus was synchronised at 15 months of age; therefore, it was not known what impact the delayed onset of oestrus for the slower growing heifers may have had on performance.

The major dairy breed categories in New Zealand are Holstein-Friesian (33.0%), Jersey (9.3%) and Holstein-Friesian-Jersey crossbred (FxJ; 48.0%) (Livestock Improvement

Corporation & DairyNZ 2017); with a large range of Holstein-Friesian and Jersey breed proportions within the FxJ breed. The growth pattern of Holstein-Friesian, Jersey and FxJ heifers differed throughout the rearing phase (Chapter 2), indicating that there may be breed-specific optimum LWTs to yield maximum performance. In addition, throughout the majority of LWTs studied, heifers of differing breed makeup (F, FX, FJ, JX or J) produced similar quantities of milk when they were the same LWT precalving (Chapter 3). There are no such studies comparing stayability of heifers of varying breed makeup at similar LWT.

Results from Chapter 3 demonstrated that heifers that were heavier throughout the precalving phase produced more milk in first lactation and accumulated over the first three lactations compared with heifers that were lighter. It was hypothesised that the three-parity production advantage that heavier heifers had over lighter heifers may have been due to superior survival of the heavier heifers, resulting in a greater number of lactations completed (Chapter 3). In addition, the growth of New Zealand dairy heifers follows the seasonal variation in pasture quality and quantity (Handcock et al. 2016; McNaughton & Lopdell 2012) (Chapter 2). Results from Chapter 4 indicated that heifers that were similar in LWT at 21 months of age but did a greater proportion of their growth in their first year of life compared with second year, produced more milk in first lactation and accumulated over three-parities compared with heifers that were a lower proportion of their 21-month LWT at 12 months of age. It is not known what effect growth pattern up to 12 and 21 months of age has on survival in the herd.

There are minimal studies quantifying the survival benefits of growing heifers heavier, or closer to target LWT. In addition, there are no studies comparing the effect of heifer LWT or growth pattern on stayability among various breeds, particularly in the New Zealand context. The aims of the current study were firstly, to explore the relationships between premating LWT and stayability and secondly, to determine the effect of differences in growth pattern up to 12 months and 21 months of age on stayability of New Zealand dairy heifers of varying breed makeup.

5.3 Materials and methods

5.3.1 Initial dataset

The initial dataset of growth curves from 189,936 heifers from Chapter 2 was used for this study. Based on pedigree information heifers were classified into one of five breed groups; Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Jersey (J), Jersey crossbred (JX) or Holstein-Friesian-Jersey crossbred (FJ; Chapter 3). Using the regression coefficients from the growth curves, LWTs were predicted for each heifer at six, 12, 15 and 21 months of age in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

Heifers were further grouped into quintiles for LWT at 21 months of age (tiny, small, average, big and huge), within breed group, using the RANK procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The proportion of LWT achieved at 12 months of age with respect to LWT at 21 months of age (pctLWT21) was calculated for each animal (Chapter 4). The number of heifers and the range in 21-month LWTs for each LWT category are displayed in Chapter 4.

5.3.2 Stayability and marginal stayability dataset

Calving dates between 1st June 2008 and 31st December 2017 were extracted from the Livestock Improvement Corporation database and merged with the initial dataset from Chapter 2. A heifer was considered successful and coded "1" if she calved between June and December of each year studied. A heifer was coded "0" (failure) if she had the opportunity to calve (old enough to have had the required number of calving events) but did not, additionally, these heifers were not considered in subsequent years. For first calving (C2yo), heifers that calved between June and December at approximately two years of age (21-29 months of age) were considered successful and coded "1" for C2yo (n=175,142; Table 5.1), heifers that did not meet these criteria were considered unsuccessful and coded "0" for C2yo (n=14,794). From the 175,142 heifers that calved as two-year-olds, heifers that had a second calving at three years of age (C3yo) were coded "1" for C3yo (n=143,696; Table 5.1), and those that did not were coded "0" for C3yo (n=31,446). This process was repeated one further time for third calving at four years of age (C4yo).

Stayability was measured from the original dataset from Chapter 2 (n=189,936) of heifers that had at least two LWT records between birth and 12 months of age and at least two LWT records between 12 months of age and first calving. These heifers were termed "heifers that were reared". For example: Stayability to second calving as a three-year-old (C3yo) was measured as proportion that calved as three-year-olds, provided they were reared P(C3yo). Likewise, for proportion that calved as four-year-olds P(C4yo).

Marginal stayability was measured as follows: given an animal's presence at a particular calving 'n', what was the probability of being present at the subsequent calving 'n+1'. For example: Marginal stayability to second calving as a three-year-old was measured as proportion that calved as a three-year-old, provided they calved as a two-year-old P(C3yo|C2yo). Likewise, for proportion that calved as four-year-olds; P(C4yo|C3yo).

Table 5.1 Number of Holstein-Friesian (F), Holstein-Friesian-crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ) Jersey crossbred (JX) and Jersey (J) heifers born between spring 2006 and spring 2013 (reared) with recorded calving dates between spring 2008 and spring 2017.

	Reared	C2yo[1]	C3yo[1]	C4yo[1]
F	48,026	44,351	35,600	27,962
FX	62,400	57,883	47,742	38,649
FJ	42,885	39,517	32,909	27,141
JX	24,218	22,187	18,355	15,118
J	12,407	11,204	9,090	7,364
Total	189,936	175,142	143,696	116,234

[1]C2yo=first calving as a two-year-old, C3yo=second calving as a three-year-old, and C4yo=third calving as a four-year-old.

5.3.3 Statistical analysis

Data were analysed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

Least squares means for each breed group were obtained using mixed models based on a binomial distribution and using a logit-transformation. The models included the fixed effect of breed group (F, FX, FJ, JX, J), the covariate deviation from median date of birth (within herd-year) and the random effect of herd-year. Herd-year was defined as the herd and year at which the heifer started her first lactation. The model for marginal stayability also included the deviation from median date of calving the year prior.

The effects of LWT on STAY and MSTAY were analysed using the same mixed models as above with the addition of the linear and quadratic effects of LWT within breed group. The LWT at which the maximum STAY and MSTAY for each breed group occurred was estimated using the ESTIMATE statement within the GLIMMIX procedure of SAS in one kg increments of LWT, using mean values for deviation from median date of birth and date of calving, for variables for which the quadratic effect of LWT on STAY or MSTAY was significant.

The model for the effects of pctLWT21 on STAY and MSTAY included the fixed effect of breed group (F, FX, FJ, JX, J), LWT category (tiny, small, average, big, huge) nested within breed group, the linear and quadratic effects of pctLWT21 nested within each combination of breed group and LWT category, the covariate deviation from median date of birth (within herd-year), and the random effect of herd-year. The model for marginal stayability also included the deviation from median date of calving the year prior.

The ESTIMATE statement within the GLIMMIX procedure of SAS was used to predict STAY or MSTAY for heifers at different proportions of 21-month LWT at 12 months of age. Confidence intervals at the 95% level ($\mu \pm 1.96$ standard error) were used to test for differences for heifers at different pctLWT21.

5.4 Results

5.4.1 Breed groups

The stayability to first calving of FX heifers was greater (93.4%; $P<0.05$) than that of FJ, JX and J heifers (Table 5.2). The stayability to first calving of F heifers was similar ($P>0.05$) to that of FX and FJ, but greater ($P<0.05$) than that of JX and J heifers (Table 5.2). Jersey heifers had the lowest stayability to all three ages studied (91.1%, 72.8% and 58.1% for C2yo, C3yo and C4yo, respectively), although stayability to third calving as a four-year-old of F heifers was 58.8% and not different ($P>0.05$) to J heifers (Table 5.2). The marginal stayability from two-year-old to three-year-old was lowest for F and J heifers (80.9% and 81.1%, respectively), intermediate for FX and JX (83.0%) and greatest for FJ heifers (83.8%; Table 5.2). Marginal stayability from three-year-old to four-year-old followed the same trend.

Table 5.2 Least squares means ± SEM for stayability (proportion calved out of proportion reared) and marginal stayability (proportion calved provided they calved the year prior) for Holstein-Friesian (F), Holstein-Friesian-crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ) Jersey crossbred (JX) and Jersey (J) cows.

	F	FX	FJ	JX	J
Stayability[1] (%)					
C2yo	$93.2^{cd} \pm 0.2$	$93.4^{d} \pm 0.2$	$93.0^{c} \pm 0.2$	$92.5^{b} \pm 0.2$	$91.1^{a} \pm 0.4$
C3yo	$74.6^{b} \pm 0.3$	$76.8^{d} \pm 0.3$	$77.1^{d} \pm 0.3$	$75.9^{c} \pm 0.4$	$72.8^{a} \pm 0.6$
C4yo	$58.8^{a} \pm 0.4$	$62.3^{b} \pm 0.3$	$63.5^{c} \pm 0.3$	$62.2^{b} \pm 0.4$	$58.1^{a} \pm 0.7$
Marginal Stayability (%)					
C3yo|C2yo	$80.9^{a} \pm 0.3$	$83.0^{b} \pm 0.2$	$83.8^{c} \pm 0.2$	$83.0^{b} \pm 0.3$	$81.1^{a} \pm 0.5$
C4yo|C3yo	$79.9^{a} \pm 0.3$	$81.9^{b} \pm 0.2$	$83.1^{c} \pm 0.3$	$82.9^{b} \pm 0.3$	$81.2^{a} \pm 0.5$

[a – d]Values within row with different superscripts differ between breed groups (P<0.05).
[1]C2yo=first calving as a two-year-old, C3yo=second calving as a three-year-old, and C4yo=third calving as a four-year-old.

5.4.2 Stayability

5.4.2.1 Live weight effects on stayability

Live weight at six, 12 and 15 months of age had significant linear and quadratic effects on stayability for all breed groups other than J (Appendix IV). The linear and quadratic effects of six-month LWT was not significant for J heifers for stayability to first calving, but both linear and quadratic effects of six-, 12- and 15-month LWT were significant for stayability to second and third calving for J (Appendix IV). When significant, the linear effects were positive, and the quadratic effects were negative (Appendix IV). In general, as LWT increased, the stayability increased up to a maximum where further increases in LWT did not result in an increased stayability. The LWT at which maximum stayability occurred was within the LWT range of each breed group studied (Table 5.3). For example, the maximum stayability to first, second and third calvings with respect to 15-month LWT was 94.3%, 79.9% and 66.0%, respectively for FJ heifers (Table 5.3). The corresponding LWT at which maximum stayability occurred at were 335 kg, 342 kg and 333 kg at 15 months of age for stayability to first, second and third calvings, respectively (Table 5.3).

For 15-month-old FJ heifers, the mean stayability to first calving was less than 90% at LWTs below 255 kg and above 415 kg (Figure 5.1 and Table 5.3). Likewise, the mean stayability to second calving was less than 75% at LWTs below 273 kg and above 411 kg, and at LWTs below 263 kg and above 402 kg, mean stayability to third calving was less than 60% (Figure 5.1 and Table 5.3). Thereby demonstrating a large range in 15-month LWTs where stayability was high. For F heifers, 15-month LWT above 274 kg resulted in stayability to first calving above 90%, there was no upper limit within the LWT range studied, where stayability was less than 90% (Table 5.3).

Similar results were found for FJ heifers at six and 12 months of age, and other breed groups studied (Appendix IV and Table 5.3).

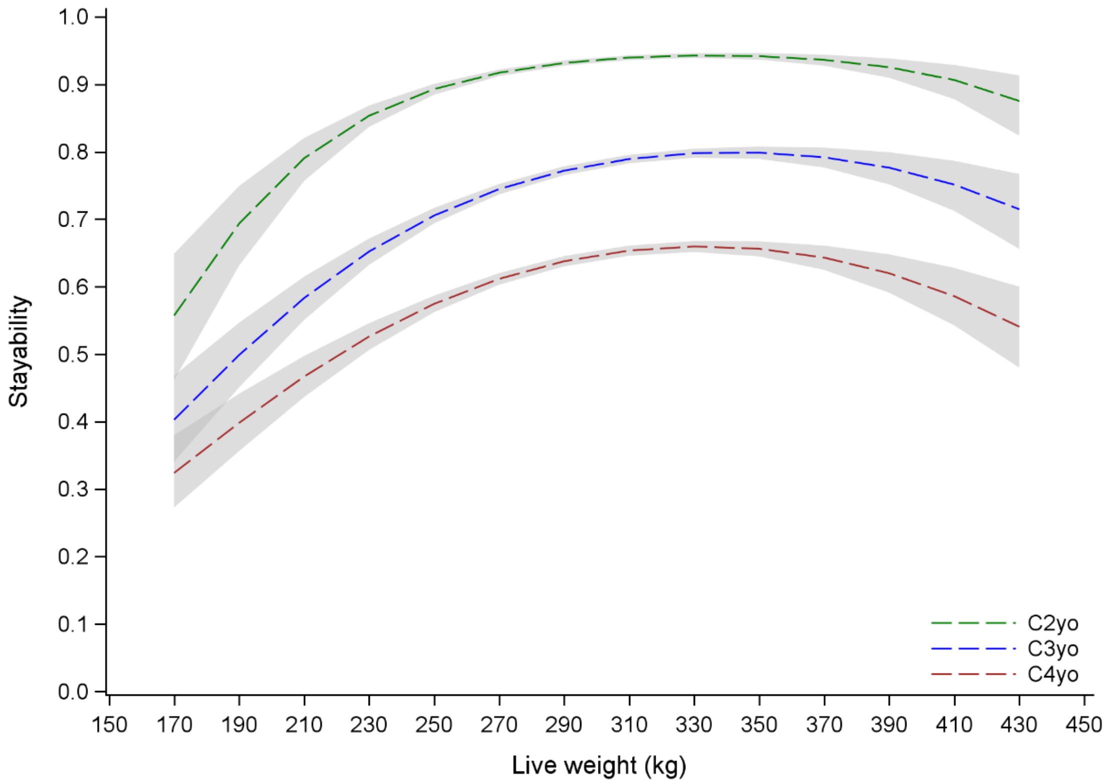

Figure 5.1 Relationship between live weight (LWT) at 15 months of age and stayability of Holstein-Friesian-Jersey crossbred (FJ) heifers that calved as two-year-olds (C2yo), three-year-olds (C3yo) or four-year-olds (C4yo) provided they were reared. Shaded area indicates 95% confidence intervals.

Table 5.3 The 15-month live weight (LWT) at which the quadratic equation predicting the effect of LWT on stayability (STAY) reached a maximum for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers and the range of LWTs where STAY to calving as a two-year-old P(C2yo) was above 90%, three-year-old P(C3yo) was above 75% and four-year-old P(C4yo) was above 60%.

Breed group and age		Max	LWT (kg) at max	Range of LWTs (kg) where STAY was:	
F					
	P(C2yo)	95.0%	367	above 90%	274 – NA*
	P(C3yo)	77.9%	363	above 75%	310 - 416
	P(C4yo)	62.0%	352	above 60%	314 - 390
FX					
	P(C2yo)	95.0%	349	above 90%	263 - 421
	P(C3yo)	79.1%	343	above 75%	280 - 407
	P(C4yo)	64.5%	336	above 60%	275 - 398
FJ					
	P(C2yo)	94.3%	335	above 90%	255 - 415
	P(C3yo)	79.9%	342	above 75%	273 - 411
	P(C4yo)	66.0%	333	above 60%	263 - 402
JX					
	P(C2yo)	93.6%	316	above 90%	248 - 385
	P(C3yo)	77.7%	312	above 75%	267 - 357
	P(C4yo)	64.3%	313	above 60%	259 - 366
J					
	P(C2yo)	91.8%	291	above 90%	238 - 345
	P(C3yo)	75.3%	301	above 75%	286 - 316
	P(C4yo)	60.8%	294	above 60%	274 - 314

*NA is where STAY was not below 90% within the LWT range studied.

5.4.2.1 Effects of proportion of 21-month LWT at 12 months of age on stayability

Figure 5.2 displays the relationship between pctLWT21 and stayability to first, second or third calving for FJ heifers that were either tiny, average or huge at 21 months of age. The relationships were curvilinear, where increases in pctLWT21 resulted in increases in stayability up to a maximum, where further increases in pctLWT21 resulted in a decrease in stayability (Figure 5.2). Average FJ heifers that were a greater proportion of their 21-month LWT at 12 months of age had greater stayability to first calving up to 57% of 21-month LWT, after which, stayability declined (Figure 5.2). Likewise, up to 59% of 21-month LWT, average FJ heifers that were a greater proportion of their 21-month LWT at 12 months of age had greater stayability to second and third calving compared with average FJ heifers that were less than 59% of their 21-month LWT (Figure 5.2). Similarly, stayability to first calving increased for tiny and huge FJ heifers that were up to 57% and 55% of their 21-month LWT, respectively (Figure 5.2). Although the proportion of 21-month LWT at which maximum stayability was reached were similar for the LWT categories, the maximum stayability for each LWT category differed in that stayability to first calving for tiny FJ heifers was 91.8% at maximum, whereas average FJ heifers was 93.6% and huge FJ heifers was 96.3% (Figure 5.2).

Similar relationships were found for the other breed groups studied, and other 21-month LWT categories within breed group (Appendix IV). Due to lower numbers of records at the extremes for pctLWT21, results are presented for heifers that were between 40 and 70% of 21-month LWT at 12 months of age (Figure 5.2).

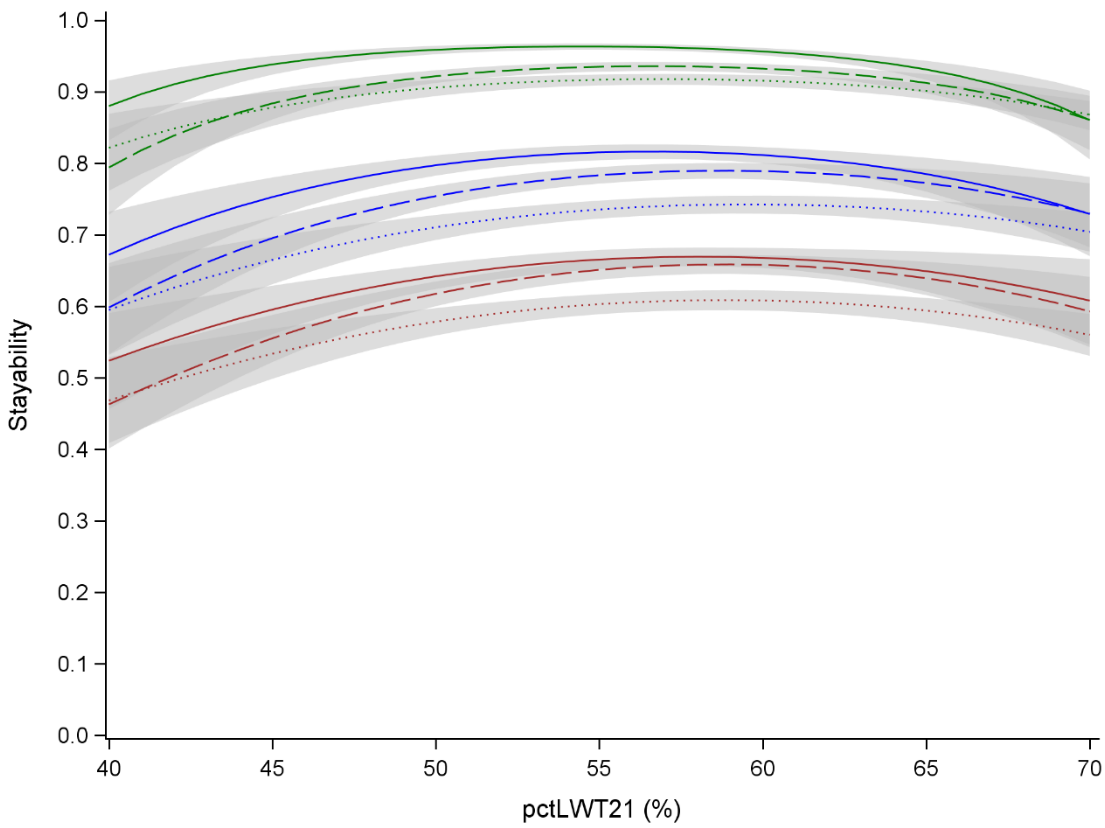

Figure 5.2 Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and stayability to calving as a two-year-old (C2yo; green lines), three-year-old (C3yo; blue lines) or four-year-old (C4yo; red lines) provided they were reared for Holstein-Friesian-Jersey crossbred (FJ) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.

Results for heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age for stayability to calving as two-, three- or four-year-olds are presented in Table 5.4, for heifers that were average in LWT at 21 months of age for their breed group. Results for tiny, small, big and huge heifers of all breed groups are presented in Appendix IV.

Based on the 95% confidence intervals, F, FX and FJ heifers that were 45% or 65% of their 21-month LWT at 12 months of age had similar stayabilities to calving as two-year-olds that were less than that of heifers that were 55% of their 21-month LWT at 12 months of age (Table 5.4). Further emphasizing the curvilinear relationship displayed in Figure 5.2. For average JX heifers, those that were 55% of their 21-month LWT at 12 months of age had greater stayability to first calving compared with average JX heifers that were 65% of their 21-month LWT at 12 months of age, and heifers that were 45% were not different to heifers that were 55% or 65% (Table 5.4).

Stayability to calving as a three-year-old was similar for average FJ heifers that were 55 or 65% of their 21-month LWT at 12 months of age (78.3 and 77.2%, respectively), likewise, stayability to calving as a four-year-old was similar for average FJ heifers that were 55 or 65% of their 21-month LWT at 12 months of age (65.1 and 63.9%; Table 5.4). Average FJ heifers that were further away from their 21-month LWT (45% pctLWT21) had lower stayability to second and third calving compared with heifers that were closer to their 21-month LWT (55% or 65% pctLWT21) at 12 months of age (Table 5.4).

There were no differences in stayability to second calving among average FX heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age (Table 5.4). Likewise, there were no differences in stayability to first or third calving among average J heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age (Table 5.4). In contrast, average J heifers that were further away from their 21-month LWT (45% pctLWT21) had lower stayability to second calving compared with heifers that were closer to their 21-month LWT (55% or 65%) at 12 months of age (Table 5.4). Similarly, average F heifers that were 45% of their 21-month LWT at 12 months of age had lower stayability to third calving (50.9%) compared with heifers that were 55 or 65% of their 21-month LWT at 12 months of age (60.0 and 58.8%, respectively; Table 5.4).

Table 5.4 Predicted stayability ± SEM to calving as a two- (C2yo), three- (C3yo) or four-year-old (C4yo) provided they were reared for average 21-month live weight (LWT) heifers that were 45%, 55% or 65% of their 21-month LWT at 12 months of age (pctLWT21).

Breed group	Stayability (%)		
	45% LWT21	55% LWT21	65% LWT21
F			
P(C2yo)	90.7^{a} ± 1.1	94.1^{b} ± 0.3	91.1^{a} ± 0.6
P(C3yo)	70.0^{a} ± 1.8	76.3^{b} ± 0.6	74.4^{ab} ± 0.9
P(C4yo)	50.9^{a} ± 2.0	60.0^{b} ± 0.7	58.8^{b} ± 1.0
FX			
P(C2yo)	91.4^{a} ± 0.8	94.2^{b} ± 0.3	91.2^{a} ± 0.5
P(C3yo)	74.6 ± 1.3	77.8 ± 0.5	75.6 ± 0.9
P(C4yo)	59.5^{a} ± 1.5	63.5^{b} ± 0.6	62.6^{ab} ± 1.0
FJ			
P(C2yo)	88.4^{a} ± 1.1	93.5^{b} ± 0.3	91.2^{a} ± 0.7
P(C3yo)	69.5^{a} ± 1.5	78.3^{b} ± 0.6	77.2^{b} ± 1.0
P(C4yo)	55.5^{a} ± 1.7	65.1^{b} ± 0.7	63.9^{b} ± 1.2
JX			
P(C2yo)	91.1^{ab} ± 1.1	93.8^{b} ± 0.4	91.0^{a} ± 0.9
P(C3yo)	72.6^{a} ± 1.8	79.1^{b} ± 0.8	75.8^{ab} ± 1.4
P(C4yo)	58.6^{a} ± 2.0	65.4^{b} ± 0.9	61.5^{ab} ± 1.6
J			
P(C2yo)	89.0 ± 2.2	93.1 ± 0.7	94.0 ± 0.9
P(C3yo)	62.7^{a} ± 3.4	74.8^{b} ± 1.2	74.5^{b} ± 1.8
P(C4yo)	53.8 ± 3.4	61.3 ± 1.4	61.6 ± 2.0

^{ab}Values within a row with different superscripts differ at the 95% confidence interval.

F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

5.4.3 Marginal Stayability

5.4.3.1 Live weight effects on marginal stayability

Live weight at six, 12 and 15 months of age had significant linear and quadratic effects on marginal stayability from two to three years of age for all breed groups (Appendix IV). Additionally, LWT at 12 and 15 months of age had significant linear and quadratic effects on marginal stayability from three to four years of age for all breed groups, except for JX heifers where only the linear effect of 12-month LWT was significant (Appendix IV). There was no relationship for JX and J heifers between LWT at six months of age and marginal stayability from three to four years of age, and only a linear relationship for FX heifers (Appendix IV). Similar to marginal stayability from two to three years of age, the linear and quadratic effects of six-month LWT on marginal stayability from three to four years of age was significant for F and FJ heifers (Appendix IV). When significant, the linear effects were positive, and the quadratic effects were negative (Appendix IV). As LWT increased, the marginal stayability increased up to a maximum where further increases in LWT did not result in an increased marginal stayability.

The LWT at which maximum marginal stayability occurred was within the LWT range of each breed group studied (Table 5.5). For example, the 15-month LWT at which maximum marginal stayability from two to three years of age occurred for FJ heifers was at 353 kg and was 312 kg for marginal stayability from three to four years of age (Table 5.5).

For 15-month-old FJ heifers, the marginal stayability from two to three years of age was less than 80% at LWTs below 244 kg (Figure 5.3 and Table 5.5) and from three to four years of age was below 80% for 15-month LWTs less than 201 kg or above 423 kg for FJ heifers (Figure 5.3 and Table 5.5). Thereby demonstrating that there was a range in 15-month LWTs where marginal stayability was high. Similar results were found for FJ heifers at six and 12 months of age, and other breed groups studied (Appendix IV and Table 5.5).

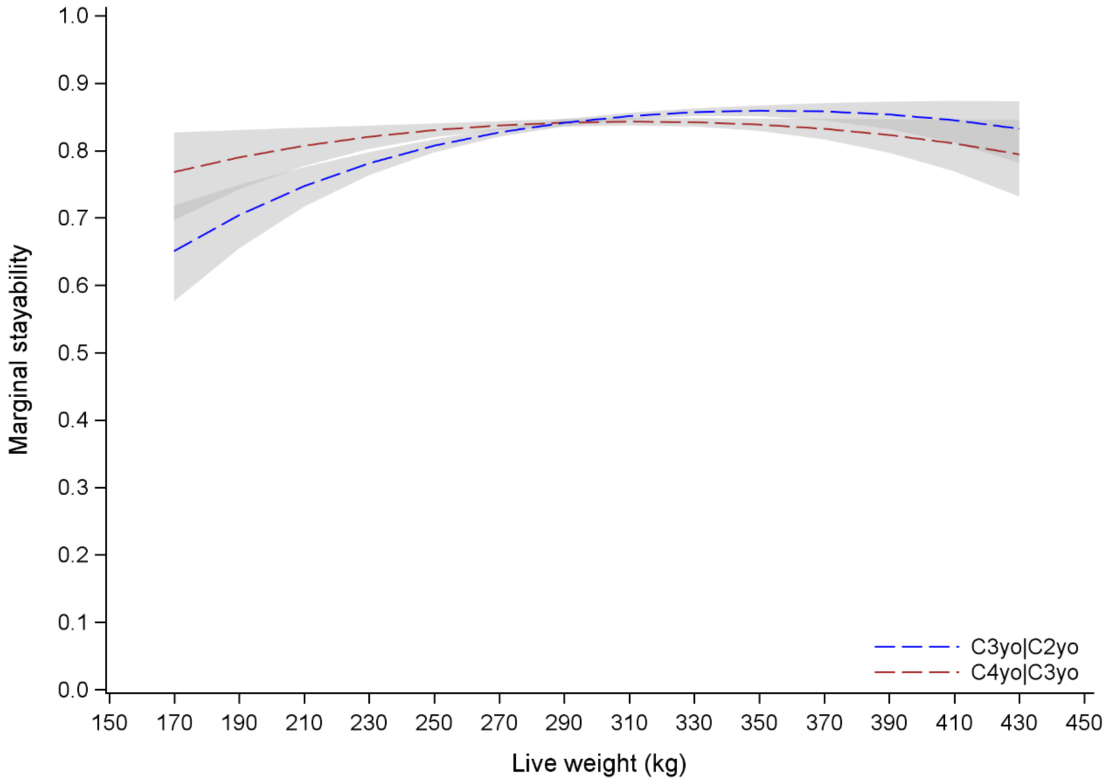

Figure 5.3 Relationship between live weight (LWT) at 15 months of age and marginal stayability of Holstein-Friesian-Jersey crossbred (FJ) heifers that calved as three-year-olds (C3yo) provided they calved as two-year-olds (C3yo|C2yo) and heifers that calved as four-year-olds (C4yo) provided they calved as three-year-olds (C4yo|C3yo). Shaded area indicates 95% confidence intervals.

Table 5.5 The 15-month live weight (LWT) at which the quadratic equation predicting the effect of LWT on marginal stayability (MSTAY) reached a maximum for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers and the range of LWTs where MSTAY to calving as a three-year-old P(C3yo|C2yo) and four-year-old P(C4yo|C3yo) were above 80%.

Breed group and age	Max	LWT (kg) at max	Range of LWTs (kg) where MSTAY was above 80%
F			
P(C3yo|C2yo)	82.7%	359	287 - 431
P(C4yo|C3yo)	81.7%	334	284 - 385
FX			
P(C3yo|C2yo)	84.2%	336	240 - 431
P(C4yo|C3yo)	83.2%	321	232 - 410
FJ			
P(C3yo|C2yo)	85.9%	353	244 - *NA
P(C4yo|C3yo)	84.3%	312	201 - 423
JX			
P(C3yo|C2yo)	84.2%	307	231 - 383
P(C4yo|C3yo)	-[1]	-	217 - 420
J			
P(C3yo|C2yo)	83.7%	308	246 - 371
P(C4yo|C3yo)	83.0%	286	228 - 343

*NA is where MSTAY was not below 80% within the LWT range studied.
[1]Quadratic effect of LWT on MSTAY was not significant so no maximum was estimated.

5.4.3.2 Effects of proportion of 21-month LWT at 12 months of age on marginal stayability

Figure 5.4 displays the relationship between pctLWT21 and marginal stayability to second and third calving for FJ heifers that were tiny, average or huge in LWT at 21 months of age. The relationships were predominantly curvilinear, where increases in pctLWT21 resulted in small increases in marginal stayability up to a maximum, where further increases in pctLWT21 did not result in further increases in marginal stayability (Figure 5.4). As evidenced by the 95% confidence intervals, marginal stayability to second and third calving was similar for average FJ heifers at similar proportions of 21-month LWT at 12 months of age (Figure 5.4). For example, average FJ heifers that were 50% of their 21-month LWT at 12 months had 82.9 ± 0.6% and 83.4 ± 0.7% probability of calving as a three- and four-year-old, respectively provided they calved the year prior (Figure 5.4).

Similar relationships were found for the other breed groups studied, and other 21-month LWT categories within breed group (Appendix IV). Due to lower numbers of records at the extremes for pctLWT21, results are presented for heifers that were between 40 and 70% of 21-month LWT at 12 months of age (Figure 5.4).

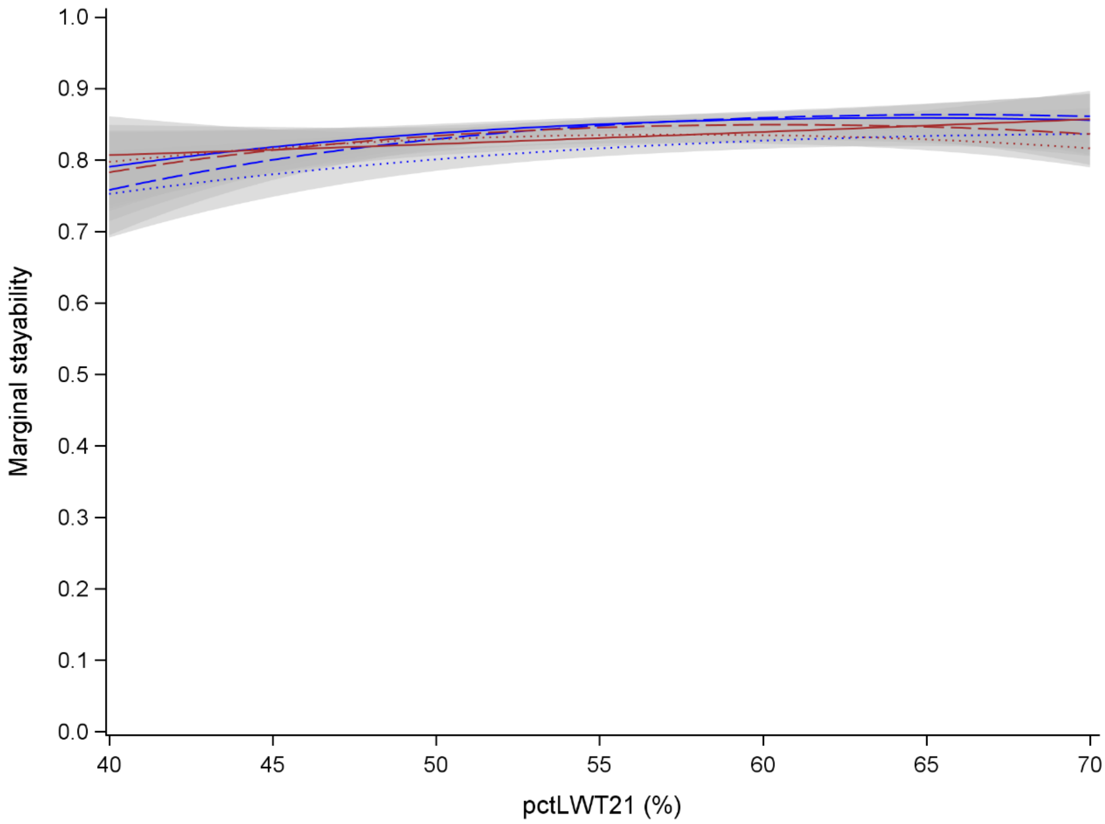

Figure 5.4 Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and marginal stayability of Holstein-Friesian-Jersey crossbred (FJ) heifers that calved as three-year-olds (C3yo) provided they calved as two-year-olds (C3yo|C2yo; blue lines) and heifers that that calved as four-year-olds (C4yo) provided they calved as three-year-olds (C4yo|C3yo; red lines) that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.

Results for heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age for marginal stayability to calving as three- or four-year-olds are presented in Table 5.6 for heifers that were average in LWT at 21 months of age for their breed group. Results for tiny, small, big and huge heifers of all breed groups are presented in Appendix IV.

Based on the 95% confidence intervals, within breed group-LWT categories, heifers that were closer to their 21-month LWT had small differences in marginal stayability compared with heifers that were further from their 21-month LWT at 12 months of age (Table 5.6). For marginal stayability from first to second calving, there were no differences among heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age for average F, FX or JX heifers. Average FJ heifers that were further (45% pctLWT21) from their 21-month LWT had a lower marginal stayability from first to second calving (79.5%) compared with average FJ heifers that were closer (55 and 65% pctLWT21) to their 21-month LWT at 12 months of age (MSTAY of 84.4 and 85.7%, respectively for 55 and 65% pctLWT21). In addition, average J heifers that were 55% of their 21-month LWT at 12 months of age had greater marginal stayability from first to second calving (81.4%) compared with average J heifers that were 45% of their 21-month LWT at 12 months of age (72.6%), while heifers that were 65% were not different (80.4%) to heifers that were 45% or 55% (Table 5.6).

Similarly, for marginal stayability from second to third calving, there were no differences among heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age for average FX, FJ, JX or J heifers (Table 5.6). Only F heifers displayed differences among heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age; average F heifers that were 45% of their 21-month LWT at 12 months of age had a lower marginal stayability from second to third calving (73.8%) compared with average F heifers that were 55 or 65% of their 21-month LWT at 12 months of age (79.2 and 79.7%, respectively; Table 5.6).

Table 5.6 Predicted marginal stayability ± SEM to calving as a three-year-old P(C3yo|C2yo) and four-year-old P(C4yo|C3yo) for heifers of average 21-month live weight (LWT) that were 45%, 55% or 65% of their 21-month LWT at 12 months of age (pctLWT21).

Breed group and LWT category	Marginal stayability (%)		
	45% LWT21	55% LWT21	65% LWT21
F			
P(C3yo|C2yo)	78.8 ± 1.7	81.6 ± 0.5	82.6 ± 0.8
P(C4yo|C3yo)	73.8^{a} ± 2.1	79.2^{b} ± 0.6	79.7^{b} ± 0.9
FX			
P(C3yo|C2yo)	83.1 ± 1.2	83.1 ± 0.5	84.1 ± 0.8
P(C4yo|C3yo)	80.4 ± 1.4	82.1 ± 0.5	83.4 ± 0.8
FJ			
P(C3yo|C2yo)	79.5^{a} ± 1.4	84.4^{b} ± 0.5	85.7^{b} ± 0.9
P(C4yo|C3yo)	80.2 ± 1.6	83.6 ± 0.6	83.5 ± 1.0
JX			
P(C3yo|C2yo)	80.8 ± 1.6	85.0 ± 0.7	84.4 ± 1.2
P(C4yo|C3yo)	81.5 ± 1.8	83.3 ± 0.8	81.8 ± 1.4
J			
P(C3yo|C2yo)	72.6^{a} ± 3.1	81.4^{b} ± 1.1	80.4^{ab} ± 1.6
P(C4yo|C3yo)	86.8 ± 2.8	82.8 ± 1.2	84.4 ± 1.8

Values within a row with different superscripts differ at the 95% confidence interval.
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

5.5 Discussion

There were significant impacts of premating LWTs and growth pattern on stayability for all breed groups studied. As LWT at six, 12 and 15 months of age increased, stayability to first calving increased up to a maximum where further increases in LWT did not result in an increased stayability. Likewise, for stayability to second and third calving, heifers that were heavier were more likely to calve as three- and four-year-olds compared with heifers that were lighter at six, 12 and 15 months of age up to a maximum. In addition, the growth pattern in which heifers reached their 21-month LWT had an impact on stayability. The relationships were curvilinear; heifers that were 55% of their 21-month LWT at 12 months of age had better stayability to first, second and third calving than heifers that were a lesser (45%) or greater (65%) proportion of their 21-month LWT at 12 months of age.

Stayability to second calving is a function of stayability to first calving in addition to marginal stayability from first to second calving. As well as heifer LWT having a significant effect on stayability to second calving through its effects on stayability to first calving, LWT effects on marginal stayability were also significant. As LWT increased, marginal stayability increased up to a maximum beyond which further increases in LWT did not result in an increased marginal stayability. These results indicate that heifer LWT has carryover impacts on probability of calving in later years. Archbold et al. (2012) reported that more of the Holstein-Friesian heifers that were heavier at first mating were present at the beginning of first (93% vs 82%) and second (76% vs 62%) lactation compared with the lighter heifers. Results from the current study support those found in Holstein-Friesian heifers by Archbold et al. (2012), in that LWT had a positive impact on probability of calving in subsequent years for Jerseys, Holstein-Friesians and their crossbreds. Furthermore, there were small impacts of pctLWT21 on marginal stayability from first to second and second to third calving. When significant, marginal stayability was better for heifers that were grown closer (55 or 65% pctLWT21) to their 21-month LWT compared with those that were further from their 21-month LWT at 12 months of age (45% pctLWT21). These results indicate that increased growth in the first year of life compared with the second year may be beneficial to marginal stayability of dairy heifers.

On average, 92.2% of heifers that were reared, successfully calved for the first time as two-year-olds in the current study. Several studies based in the United Kingdom reported that between 85.5% and 89% of Holstein-Friesian heifers survived from birth to first calving (Brickell et al. 2009b; Cooke et al. 2013; Pritchard et al. 2013). The proportion of heifers that had a first calving in the current study was greater than that reported by the United Kingdom studies. The studies by Brickell et al. (2009b) and Cooke et al. (2013), followed heifers from birth until first calving, therefore, they were able to capture the early-in-life losses. Heifers that were selected for inclusion in the original LWT dataset (Chapter 2) were required to have multiple LWT records spread between birth and 12 months of age, and 12 to 24 months of age. Therefore, early-in-life losses due to disease, illness and other causes would not have been captured in the dataset for the current study. Furthermore, a New Zealand study of naturally mated heifers reported that 7.3% of heifers that were mated (n=7,053), failed to calve as two-year-olds (MacMillan 1994), very similar to the 7.8% reported in the current study with a much larger dataset (n=189,936). The estimate of stayability to first calving for the current study may be an overestimate of heifer survival and may in fact be a comparable measure to whether a heifer gets pregnant or not. Meier et al. (2017) reported that the loss of Holstein-Friesian heifers from nine days of age to 17 months of age for a New Zealand research herd was 4.8% and 9.8%, for heifers that were of high or low genetic merit for fertility, respectively. Addition of the results reported in the current study with those from Meier et al. (2017) would put heifer losses in the range of 12.6 and 17.6%, similar to that reported by Brickell et al. (2009b) and Cooke et al. (2013) for British heifers.

Stayability to second and third calving are more complex traits compared with stayability to first calving. They are the combinations of stayability to first calving in addition to factors affecting reproductive success and survival during lactation. The most common reasons for culling cows during lactation was reported to be reproductive-related, followed by “other” (Compton 2018). In addition, Compton (2018) reported that the most common reason for selling cows during lactation was also for reproductive-related reasons. Animals that fail to conceive in the short mating period will not begin a new lactation in the following season. Furthermore, because it is costly to feed these nonpregnant cows without any return from milk, the majority are culled or sold (Compton 2018). Kerslake et al. (2018) reported that the most common cause of removal (cull, sold or death) from the New Zealand dairy herd was for reproductive reasons (abortion, non-pregnant or low fertility; 34.9% of removals) followed closely by “unknown” reasons (29.2%). As mentioned previously, recording fates of dairy cows in the New Zealand system is voluntary, and large proportions of cows that were considered for the study by Kerslake et al. (2018) had missing dates and/or reasons for removal (43%; n=6,988,011 out of 16,399,396 considered). For this reason, the present study considered a calving event as a measure of cow survival as it does not require recording of cull data.

The marginal stayability of heifers from first to second calving was approximately 82%; similar to 81% of first calving heifers in the United Kingdom reported by Brickell and Wathes (2011) and 84.1% of New Zealand two-year-olds were milked as three-year-olds (Livestock Improvement Corporation & DairyNZ 2017). In addition, approximately 24% and 39% of heifers that were reared, failed to remain in the herd to calve a second or third time, respectively. This is comparable to 45% of animals recruited for a study at one month of age not surviving to calve a third time (Brickell & Wathes 2011). A study in Great Britain revealed that the mean time the costs to rear a heifer were repaid was 530 days (1.5 lactations) before becoming profitable for the farm (Boulton et al. 2017). The study by Boulton et al. (2017) was based on a mix of year-round and seasonal calving systems and assumed a 305-day lactation each year. It is therefore likely that in the New Zealand system where the average lactation is 276 days (Livestock Improvement Corporation & DairyNZ 2017), the length of time for a heifer to become profitable may be longer than that reported by Boulton et al. (2017) due to less productive days per lactation. There are substantial differences between the British and New Zealand farming systems, additionally, there are no published studies based on the New Zealand system of the time taken to repay the costs of rearing a heifer. Therefore, application of the results from Boulton et al. (2017) should be done so cautiously. Nevertheless, results from the current study indicate that improvements to stayability, and hence profitability could be made by rearing lighter heifers to heavier LWTs in the first 12 months and prior to first mating. This would be achieved through the greater stayability to first calving of heavier heifers in addition to the greater marginal stayability from first to second, and second to third calving.

There was an overlap in the range in LWT where stayability and marginal stayability were “good” for all breed groups studied. For FJ heifers, this overlapping range was between 273 and 402 kg at 15 months of age; the majority (80.5%) of FJ heifers were within this range, only 0.1% were greater than 402 kg and 19.3% were less than 273 kg. Therefore, less than 20% of FJ heifers had 15-month LWTs where they were “at risk” of having poor stayability, the majority of which were lighter, indicating improvements to stayability could be made by growing these lighter heifers heavier.

Results presented in Chapter 3 showed that heifers that were heavier produced more milk in first lactation and accumulated over three parities compared with heifers that were lighter. It was hypothesised that the three-parity production advantage that heavier heifers had over lighter heifers may have been due to superior survival of the heavier heifers, resulting in a greater number of lactations completed (Chapter 3). The difference in stayability between the very light and the mid-range heifers reported in the current study provides evidence supporting this hypothesis that very light heifers were less likely to survive, and therefore complete less lactations compared with heifers in the mid-range for LWT. The lightest heifers in the current study produced the least milk in first lactation (Chapter 3), it is possible that these lighter, low producing heifers may have been removed from the herd due to low milk production. The proportion of cows removed from the New Zealand herd due to low milk production was 8.6% of removals (Kerslake et al. 2018), however, the most common reason for removal from the herd was for reproductive reasons (34.9%). A recent study based in Ireland reported that growth rate from birth to first mating had a linear relationship with heifer fertility, as measured by the interval (in days) from PSM to conception (Hayes et al. 2019). Heifers that grew slower between birth and PSM had a longer interval between PSM and conception compared with heifers that grew faster (Hayes et al. 2019), therefore, the lightest heifers may have been removed for reasons related to reproduction such as late calving.

Results from the present study demonstrated that heifers that were very heavy for their breed group were less likely to survive each year compared with heifers in the mid-range for LWT. Ferrell (1982) reported that heifer body condition score (BCS) had a curvilinear relationship with pregnancy rates of beef heifers. Ferrell (1982) determined that a BCS of 6.7 (on a 1 to 9 scale) was optimum for pregnancy rate, and that excessively thin and excessively fat heifers were at risk of having lower pregnancy rates compared with moderately conditioned heifers. As previously mentioned, the majority of nonpregnant heifers/cows are culled or sold (Compton 2018), hence low pregnancy rates directly affects stayability. Body condition score records were not available for heifers in the current study, however, it is likely that heifers at the very heavy end of the LWT range were in better condition compared with the lighter heifers, due to the positive correlation between LWT and BCS (Roche et al. 2007), which may have influenced pregnancy rates and therefore, stayability. In addition, Brickell et al. (2009a) reported that non-pregnant heifers (n=16) tended to be heavier at six months of age and were significantly heavier than pregnant heifers (n=412) at 15 months of age. However, these results should be interpreted with caution due to the low number of non-pregnant heifers spread across 16 dairy farms included in the study by Brickell et al. (2009a). Further research should be directed at understanding whether the reasons why very light and very heavy heifers in the current study failed to remain in the herd for successive calvings are due to reproductive reasons, or for other causes such as culling for low milk production.

The recommended target LWTs for New Zealand dairy heifers are 30% of mature LWT at six months of age, 60% at 15 months of age and 90% pre-calving (DairyNZ 2015a; Troccon 1993). Linear interpolation between the targets correspond to 50% at 12, and 86% at 21 months of age (DairyNZ 2015a). Based on a mature LWT of 500 kg, target LWT at 12 months of age would be 250 kg and at 21 months of age would be 430 kg. Heifers that met both of these targets would have been 58% of their 21-month LWT at 12 months of age. Results from the current study indicate that heifers that were between 55 and 60% of their 21-month LWT at 12 months of age had good stayability. Therefore, heifers grown to meet target LWTs at 12 and 21 months of age would be expected to have superior stayability compared with heifers that failed to meet target at 12 months of age but met 21-month target LWT. Thereby, indicating the importance of monitoring heifer growth throughout the rearing period (birth to first calving) to ensure heifers do not fall too far below target LWTs.

The deviation from median date of birth was included as a covariate in the analyses for stayability and marginal stayability in order to estimate the effect of LWT or pctLWT21 on the calving in question, without the effect of date of birth. Based on the results reported by Jenkins et al. (2016), it was hypothesised that being born earlier in the calving period may provide a fertility and hence stayability advantage to heifers at their first calving, which may have carryover advantages on second and third calving. Jenkins et al. (2016) reported that heifers born earlier, calved earlier than heifers born later, and postulated that being born earlier may have given the heifers the opportunity to reach puberty and mature earlier than their later-born herdmates. Despite this, there was little to no effect (-0.06 – 0.00% per day earlier) of date of birth on probability of first calving in the current study, additionally, there were only small effects (0.03 – 0.04% per day earlier) of date of birth on the likelihood of subsequent calvings. Removal of date of birth from the analyses (LWT and pctLWT21) made little difference to the models (data not shown), indicating that the benefits of increased premating LWT on stayability and marginal stayability existed regardless of how early or late the heifer was born. Further research on the effects of LWT, pctLWT21 and date of birth on earliness of calving are required to test whether fertility advantages of early-born or heavier heifers exist.

The deviation from median date of calving the year prior was included as a covariate in the analysis for marginal stayability in order to estimate the effect of LWT on the calving in question without the carryover effect of date of calving in the year prior. For all marginal stayability from first to second calving analyses (LWT and pctLWT21), the effect of date of first calving was significant and negative at 0.20% lower probability of second calving for each day later the animal calved at first calving. Likewise, for all marginal stayability from second to third calving analyses (LWT and pctLWT21), the effect of date of second calving was significant and negative at 0.33% lower probability of third calving for each day later the animal calved at second calving. Despite this, removing date of previous calving from the analysis made little difference to the models (data not shown), indicating that the benefits of increased premating LWT on marginal stayability to second or third calving were not simply mediated through how early or late the cow calved the year prior.

Breed groups differed in stayability and marginal stayability, with crossbreeds (FX, FJ and JX heifers) generally having better performance compared with straight breeds (F and J heifers). Xu and Burton (2003) reported that crossbred cows have approximately 2% greater six-week in-calf rate and 1.6% greater final in-calf rate compared with F and J cows. The superiority of crossbreds in in-calf rate may have led to better stayability of crossbreds compared with F and J in the current study. In addition, F heifers in the current study had better stayability to first and second calving to that of J heifers, but both breed groups were similar in stayability to third calving and marginal stayabilities. These results are similar to that reported by Xu and Burton (1999) that 15-month-old Friesian heifers had higher conception rates and pregnancy rates and lower nonpregnancy rates compared with Jersey heifers, and MacMillan (1994) who reported that the nonpregnancy rate for F heifers was 5.4%, whereas it was 10% for J heifers. Results from the current study also support those of Xu and Burton (1999) and Grosshans et al. (1997), where F heifers had superior performance to J heifers for first calving, whereas the performance of J cows exceeded that of F cows for second and third calving.

5.6 Conclusions

There were positive curvilinear relationships between premating LWT and stayability and marginal stayability of heifers. Heifers that were heavier at six, 12 and 15 months of age were more likely to remain in the herd for first, second and third calving compared with heifers that were lighter, regardless of breed group. Furthermore, plane of nutrition in the first year of a heifer's life was important for stayability to first, second and third calvings. Heifers that were moderately well-grown at 12 months of age relative to their 21-month LWT were more likely to remain in the herd compared with heifers that were further from their 21-month LWT at 12 months of age. For heifers that were at the heaviest end of the LWT range in the current study, there was a slight decline in stayability compared with heifers in the mid-range of LWT. Consequently, for heifers that were below average in LWT, there would be considerable benefits to stayability over the first three calvings by improving rearing practices to result in heavier heifers throughout the premating rearing phase.

Chapter 6 Calving and re-calving rate of dairy heifers as affected by live weight and growth prior to first calving

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6.1 Abstract

This study investigated the relationships between live weight (LWT) and calving pattern of 189,936 New Zealand dairy heifers. Heifers were classified into five breed groups; Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Jersey (J), Jersey crossbred (JX) and Holstein-Friesian-Jersey crossbred (FJ). Live weights (LWT) were assessed at six, 12 and 15 months of age and their relationships with calving rate and re-calving rate over the first three calvings were analysed. In addition, the relationships between proportion of LWT achieved at 12 months of age with respect to LWT at 21 months of age (pctLWT21) and calving and re-calving rates were analysed to estimate the effect of increased growth in the first year of life on reproduction. There were positive curvilinear relationships between premating LWT and reproductive performance of dairy heifers. Heifers that were heavier at six, 12 and 15 months of age were more likely to calve early for first calving compared with heifers that were lighter, regardless of breed group. In addition, there was a large range in LWT where the probability of calving or re-calving early was high. For example, for FJ heifers that were between 255 and 396 kg at 15 months of age had 21-day calving and re-calving rates above 75% and 70%, respectively. Heifers that grew slower in their first year of life and hence were further from their 21-month LWT at 12 months of age that did calve, were more likely to calve early in first lactation compared with heifers that grew faster and hence were closer to their 21-month LWT at 12 months of age. When heifers that did not calve were included as also failing to calve early (re-calving rate), heifers that were in the mid-range for pctLWT21 had the greatest probability of calving early in first lactation. For second and third lactations however, there were small impacts of heifer premating LWTs or growth pattern up to 21 months of age on the earliness of calving. For heifers that were at the heaviest end of the LWT range in the current study, there was a slight decline in reproductive performance compared with heifers in the mid-range of LWT. Consequently, for heifers that were below average in LWT, there would be reproductive benefits over the first three calvings, in particular for first calving by improving rearing practices to result in heavier heifers throughout the premating rearing phase.

6.2 Introduction

In order to maintain the close relationship between pasture supply and animal feed demand in a seasonal pasture-based system, cows must calve at the same time each year. The gestation length of dairy cattle is approximately 282 days (Donkersloot 2014; Haile-Mariam & Pryce 2019), therefore, the planned start of calving (PSC) date is determined by the planned start of mating (PSM) date. At PSM date, every cow detected in oestrus will be bred regardless of how long ago she calved. The main goal is to get as many cows pregnant as quickly as possible in order to achieve a compact calving pattern the next year. A measure of reproductive performance in seasonal-calving herds is the six-week (42-day) in-calf rate; the percentage of the herd that became pregnant within six weeks of PSM (Bowley et al. 2015). The industry target for six-week in-calf rate is 78%, and based on the targets of a 90% three-week submission rate and a 60% conception rate (Brownlie et al. 2014), the three-week in-calf rate target would be 54%. The national average for six-week in-calf rate for the 2017/18 season was 66%; 12% below the industry target (Livestock Improvement Corporation & DairyNZ 2018). Consequently, methods to improve national reproductive performance should be explored.

In-calf rates can only be determined reliably when early-aged pregnancy diagnosis are performed (Hemming et al. 2018). In large-scale analyses where early aged pregnancy diagnosis is not performed (or recorded) for all animals, the percentage of cows calving within 21 or 42 days of PSC can be estimated and used to compare reproductive performance (Brownlie 2012). Calving rates can be calculated based on animals that calved that year (calved within 21 days in year 'n' provided they calved in year 'n') or based on animals that calved the year prior (calved within 21 days in year 'n' provided they calved in year 'n-1'). For the purposes of this study, the proportion of animals that calved within 21 days provided they calved that year will be considered as "calving rate" (C21) and the proportion of animals that calved within 21 days provided they calved the year prior will be considered as "re-calving rate" (RC21). Re-calving rates can be used as a proxy measure for in-calf rates when no pregnancy diagnosis information is available (Brownlie 2012; DairyNZ 2018e). Re-calving rates should be interpreted as only estimates for in-calf rates (DairyNZ 2018e), due to the variable proportion of animals that do not calve for reasons other than failure to conceive and maintain a pregnancy. However, treating females that did not calve as missing (i.e. C21) does not account for an important source of variation in fertility (Donoghue et al. 2004), as females that failed to calve also failed to calve within 21 days.

Twenty-one and 42-day calving rates would be expected to be higher than the corresponding in-calf rates due to the removal of nonpregnant cows and culled cows before the commencement of the calving period and the inclusion of first calving heifers. For example, the mean 42-day in-calf rate was 64.4% for herds milked twice-a-day, whereas the 42-day calving rate was 83.9% for the same herds (Hemming et al. 2018), re-calving rate was not reported in that study. Additionally, industry targets for calving rates differ based on the age of the cows. Due to prolonged periods of anoestrous of first calving heifers compared with mature cows (Fonseca et al. 1983; McDougall et al. 1995), 15-month-old heifers tend to be bred earlier than the main herd to allow for all cows to be cycling at PSM. To account for these differences in mating start dates, industry targets for calving rates are 75% of first calvers calved within 21 days of PSC and 60% of the whole herd calved within 21 days of PSC (DairyNZ 2018c). Results from the national fertility monitoring project showed that 56% of cows calved within 21 days of PSC (Xu & Burton 2003), the mean for twice daily milked herds was 59% calved within 21 days of PSC (Edwards 2019).

A greater proportion of replacement heifers that calved early (within 21 days of first PSC) in their first lactation also calved early (within 42 days of second PSC) in their second lactation compared with heifers that calved later (after 21 days from first PSC) in their first lactation (Pryce et al. 2007). This relationship between earliness of calving in subsequent years emphasises the importance of early calving heifers, as they are likely to become early calving cows. In order to calve early in the calving season, heifers need to have attained puberty by, and get pregnant at 15 months of age. In an Irish study, more Holstein-Friesian heifers that were heavier at first mating were pubertal and calved earlier than heifers that were lighter at mating (Archbold et al. 2012). Therefore, it would be advantageous to have all heifers pubertal and heavier before mating.

Positive relationships between precalving LWT and milk production have been reported for New Zealand dairy heifers (McNaughton & Lopdell 2013; van der Waaij et al. 1997) (Chapter 3). Furthermore, heifers that grew more in the first year produced more milk than heifers that grew less in their first year but ended up similar in LWT at 21 months of age (Chapter 4). These results indicated that greater milk production could be achieved in the first and subsequent lactations by growing heifers to reach greater LWTs. It was hypothesised that the three-parity production advantage that heavier heifers had over lighter heifers may have been due to superior reproduction and survival of the heavier heifers, resulting in a greater number of lactations completed (Chapter 3). Results from Chapter 5 demonstrated that there were significant curvilinear relationships between heifer premating LWTs and stayability to first, second and third calvings. Heifers that were in the mid-range for LWT at six, 12 and 15 months of age were more likely to calve each year compared with heifers that were very light and heifers that were very heavy (Chapter 5). Similarly, heifers that were moderately well-grown at 12 months of age relative to their 21-month LWT were more likely to remain in the herd compared with heifers that were further from their 21-month LWT at 12 months of age (Chapter 5). Kerslake et al. (2018) reported that poor reproductive performance was the main cause of cow removal from herds in New Zealand (35% of cows culled were for reproductive reasons). It was hypothesised that a reason for lack of stayability of very light and very heavy heifers (Chapter 5) may have been due to reproductive reasons, in particular non-pregnancy (failure to conceive) and calving late.

There are minimal studies on the effects of LWT and growth on reproduction in dairy cattle (Bach 2011; Davis Rincker et al. 2011; Macdonald et al. 2005), the majority of studies focus on preweaning growth in both beef and dairy cattle, or the effects of growth (pre- and postweaning) on puberty or milk production, and not subsequent reproductive performance. For example, Raeth-Knight et al. (2009) reported that Holstein calves fed a high energy and high protein milk replacer diet from three until 56 days of age gained 0.8 kg/d during the preweaning period and calved approximately 27 days younger than calves fed a conventional milk replacer who gained 0.55 kg/d. Similarly, Holstein calves fed an intensive milk-rearing diet (high-energy, high-protein) from two to 42 days of age resulting in ADG of 0.64 kg/day, were younger (31 days) and lighter (20 kg) at puberty compared with heifer calves fed the conventional diet that grew at 0.44 kg/d (Davis Rincker et al. 2011). In addition, these intensively fed heifers tended to be 15 days younger at conception and 14 days younger at calving than heifers fed the conventional diet, although differences were not significant (Davis Rincker et al. 2011), potentially due to LWT being not different from 12 weeks of age onward. These studies indicate that preweaning growth may be important for future reproductive performance, but do not report effects of growth after weaning and up to first breeding on reproduction.

Growth rate between 100 and 200 kg or 200 kg and 22 months of age for Holstein-Friesian or between 80 and 165 kg or 165 kg and 22 months of age for Jersey heifers had no impact on first calving date, calving interval, or proportion of heifers surviving to second or third lactation (Macdonald et al. 2005). However, there were differences in the proportion of heifers cycling prior to first mating in the study by Macdonald et al. (2005) in that a lower proportion of heifers that grew slower were cycling compared with heifers that grew faster. Oestrus was synchronised at 15 months of age for all heifers; therefore, it was not possible to tell what impact the delayed onset of oestrus for the slower growing heifers may have had on final reproductive performance.

The growth of New Zealand dairy heifers follows the seasonal variation in pasture quality and quantity (Handcock et al. 2016; McNaughton & Lopdell 2012) (Chapter 2). Results from Chapter 5 indicated that heifers that were similar in LWT at 21 months of age but did a greater proportion of their growth in their first year of life compared with second year, were more likely to calve each year compared with heifers that were a lower proportion of their 21-month LWT at 12 months of age. It is not known what effect growth pattern up to 12 and 21 months of age has on reproduction, in particular calving rate or re-calving rate.

The aims of the current study were firstly, to explore the relationships between premating LWTs and calving rate and premating LWTs and re-calving rate. Secondly, to determine the effect of differences in growth pattern up to 12 months and 21 months of age on calving and re-calving rates for first, second and third calving of New Zealand dairy heifers of varying breed makeup.

6.3 Materials and methods

6.3.1 Dataset

The dataset from Chapter 5 for the analysis of stayability was used as the base dataset for the current study. This dataset contained predicted LWTs at six, 12, 15 and 21 months of age for 189,936 heifers that were one of five breed groups; Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Jersey (J), Jersey crossbred (JX) or Holstein-Friesian-Jersey crossbred (FJ; Chapter 3). Heifers were further grouped into quintiles for LWT at 21 months of age (tiny, small, average, big and huge), within breed group, using the RANK procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The proportion of LWT achieved at 12 months of age with respect to LWT at 21 months of age (pctLWT21) was calculated for each animal (Chapter 4). The number of heifers and the range in 21-month LWTs for each LWT category are displayed in Chapter 4.

6.3.2 Calving rate

To generate the calving rate dataset, PSM and PSC dates for each herd-year were extracted from the Livestock Improvement Corporation database and merged with the stayability dataset from Chapter 5. The PSM date is calculated as the first of two consecutive days, with one or more matings recorded, and where at least three of the subsequent six days have matings recorded (DairyNZ 2018e). The PSC date is calculated as 282 days after PSM date (Edwards 2019); both PSM and PSC dates are calculated and stored on the Livestock Improvement Corporation database for approximately 85% of herds (Livestock Improvement Corporation & DairyNZ 2017), according to the InCalf Fertility Focus User Guide rules (DairyNZ 2018e).

The PSM and PSC dates were merged with the individual heifer records for heifers that had a first calving (C2yo; n=175,142), second calving (C3yo; n=143,696) and third calving (C4yo; n=116,234) as three separate datasets. Heifers from herds with no PSC date for a herd-year were removed from the datasets (n=9,737 for C2yo, n=11,145 for C3yo and n=11,542 for C4yo). The interval from PSC to calving was calculated for each heifer, and heifers that calved between 47 days before PSC and 142 days after PSC for each year were selected for the analysis of 21-day calving rate (Brownlie et al. 2014), heifers outside this criteria for each calving were removed from the dataset for that calving. The start of the herd-year is defined as 130 days before mating start date (Brownlie et al. 2014), or 47 days before PSC (where mating start date is 83 days after

PSC). The upper limit for calving dates to be included is 142 days after PSC (59 days after MSD) to account for late calvers.

A heifer was coded “1” for calving rate in first 21 days (C21) if she calved within 21 days of PSC and “0” if she calved later than 21 days. The number of animals for each calving variable are outlined in Table 6.1.

Table 6.1 Number (N) of Holstein-Friesian (F), Holstein-Friesian-crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ) Jersey crossbred (JX) and Jersey (J) cows with recorded calving dates relative to their herd planned start of calving (PSC) date.

	C2yo	C3yo	C4yo
F	41,987	33,069	25,180
FX	55,159	44,413	35,120
FJ	37,020	30,089	24,251
JX	20,754	16,566	13,470
J	10,382	8,345	6,628
Total	165,302	132,482	104,649

Where C2yo is first calving as a two-year-old, C3yo is second calving as a three-year-old, and C4yo is third calving as a four-year-old.

6.3.3 Re-calving rate

For first calving heifers, “re-calving rate” was estimated from the original dataset of 189,936 heifers from Chapter 2 termed “heifers that were reared”. For example, 21-day re-calving rate for first calvers was measured as the proportion that calved within 21-days of PSC, provided they were reared. For second calvers, was the proportion of heifers that calved within 21-days of PSC, provided they calved as two-year-olds and likewise for third calving re-calving rate.

To create the dataset for re-calving rate, heifers that did not have a recorded first calving date as a two-year-old from the stayability dataset used in Chapter 5 (n=14,794), but were from herds with PSC information (n=13,161) were coded “0” for RC21_2yo and were merged with the dataset from Table 6.1. Likewise, heifers that did not have a recorded second calving date as a three-year-old (n=31,446) but were from herds with PSC information (n=28,868) were coded “0” for RC21_3yo and were merged with the dataset from Table 6.1. Finally, heifers that did not have a recorded third calving date as a four-year-old (n=27,462) but were from herds with PSC information (n=24,529) were coded “0” for RC21_4yo and were merged with the dataset from Table 6.1. The number of animals included for each re-calving dataset are outlined in Table 6.2.

Table 6.2 Number (N) of Holstein-Friesian (F), Holstein-Friesian-crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ) Jersey crossbred (JX) and Jersey (J) cows with re-calving rate data.

	C2yo	C3yo	C4yo
F	45,248	41,133	32,050
FX	59,266	53,780	43,327
FJ	40,056	36,146	29,338
JX	22,509	20,046	16,356
J	11,384	10,245	8,107
Total	178,463	161,350	129,178

Where C2yo is first calving as a two-year-old, C3yo is second calving as a three-year-old, and C4yo is third calving as a four-year-old.

6.3.4 Statistical Analysis

Data were analysed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

Least squares means of dependent variables for each breed group were obtained using mixed models based on a binomial distribution and using a logit-transformation. The models included the fixed effect of breed group (F, FX, FJ, JX, J), the covariate deviation from median date of birth (within herd-year) and the random effect of herd-year. For second (C3yo) and third (C4yo) calving and re-calving rates the deviation from median date of calving the year prior was added to the models.

The effects of LWT on reproductive parameters were analysed using the same mixed models as above with the addition of the linear and quadratic effects of LWT within breed group. The LWT at which the maximum calving or re-calving rate for each breed group occurred was estimated using the ESTIMATE statement within the GLIMMIX procedure of SAS in one kg increments of LWT, using mean values for deviation from median date of birth and date of calving, for variables for which the quadratic effect of LWT on calving or re-calving rate was significant.

The model for the effects of pctLWT21 on calving or re-calving rate included the fixed effect of breed group (F, FX, FJ, JX, J), LWT category (tiny, small, average, big, huge) nested within breed group, the linear and quadratic effects of pctLWT21 nested within each combination of breed group and LWT category, the covariate deviation from median date of birth (within herd-year), and the random effect of herd-year. The model for second (C3yo) and third (C4yo) calving also included the deviation from median date of calving the year prior.

The ESTIMATE statement within the GLIMMIX procedure of SAS was used to predict calving or re-calving rate for heifers at different proportions of 21-month LWT at 12 months of age. Confidence intervals at the 95% level ($\mu \pm 1.96$ standard error) were used to test for differences for heifers at different pctLWT21.

6.4 Results

6.4.1 Breed groups

Crossbred heifers (FX, FJ and JX) had greater proportions of heifers calved within 21 days of PSC as two-year-olds compared with F and J heifers, which were no different to each other (Table 6.3). Holstein-Friesian heifers had a lower 21-day calving rate as three-year-olds (60.1%) and four-year-olds (56.6%) compared with FX heifers (62.3% and 58.5% for three- and four-year-old, respectively). The proportions of heifers that calved within 21 days of PSC as three-year-olds did not differ among FJ, JX and J heifers (Table 6.3). Likewise, the 21-day calving rate as four-year-olds also did not differ among FJ, JX and J heifers (Table 6.3).

Re-calving rates by breed group were lower than the respective calving rates by breed group (Table 6.3). Twenty-one-day re-calving rate for first-calving FX, FJ and JX heifers was greater than 21-day re-calving rate for first-calving J heifers (Table 6.3). In addition, more F heifers re-calved early than J heifers but were no different to JX heifers (Table 6.3). Furthermore, J cows had greater re-calving rates for second and third calving compared with F cows, likewise, more FX cows calved early for second and third calving compared with F cows (Table 6.3). The breed group with the greatest re-calving rate for second calving was FJ; 4.7% greater than re-calving rates of F cows. For third calving, similar proportions of FJ and JX cows re-calved early but more than F and FX cows (Table 6.3).

Table 6.3 Least squares means (± SEM) for 21-day calving rate (calved within 21 days of planned start of calving, provided they calved; C21) and 21-day re-calving rate (calved within 21 days of planned start of calving, provided they calved the year prior; RC21) for Holstein-Friesian (F), Holstein-Friesian-crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ) Jersey crossbred (JX) and Jersey (J) cows.

	F	FX	FJ	JX	J
Calving rate (%)					
C21_2yo	$80.0^{a} \pm 0.3$	$81.2^{b} \pm 0.3$	$81.2^{b} \pm 0.3$	$81.1^{b} \pm 0.4$	$79.6^{a} \pm 0.6$
C21_3yo	$60.1^{a} \pm 0.4$	$62.3^{b} \pm 0.3$	$63.3^{c} \pm 0.4$	$62.8^{bc} \pm 0.5$	$62.5^{bc} \pm 0.7$
C21_4yo	$56.6^{a} \pm 0.4$	$58.5^{b} \pm 0.4$	$60.2^{c} \pm 0.4$	$59.9^{c} \pm 0.5$	$59.0^{bc} \pm 0.8$
Re-calving rate (%)					
RC21_2yo†	$73.9^{b} \pm 0.3$	$75.2^{c} \pm 0.3$	$74.8^{c} \pm 0.3$	$74.6^{bc} \pm 0.4$	$71.9^{a} \pm 0.7$
RC21_3yo	$48.0^{a} \pm 0.4$	$51.2^{b} \pm 0.3$	$52.4^{c} \pm 0.4$	$51.3^{b} \pm 0.4$	$50.3^{b} \pm 0.7$
RC21_4yo	$44.4^{a} \pm 0.4$	$47.1^{b} \pm 0.4$	$49.1^{d} \pm 0.4$	$48.6^{cd} \pm 0.5$	$47.2^{bc} \pm 0.8$

where C2yo is first calving as a two-year-old, C3yo is second calving as a three-year-old, and C4yo is third calving as a four-year-old.
†RC21_2yo represents heifers that calved early, provided they were reared.
$^{a-d}$Means within row with different superscripts differ between breed groups (P<0.05).

6.4.2 Liveweight effects

6.4.2.1 Calving rate

First calving 21-day calving rate was more affected by LWT at six, 12 and 15 months of age compared with second and third 21-day calving rates (Appendix V). When significant, the linear effects of LWT were positive and the quadratic effects were negative (Appendix V). As LWT increased, the probability of calving within 21 days increased up to a maximum where further increases in LWT did not result in an increased probability of calving early. In addition, for J, JX and FX heifers, there was no age at which the relationship between LWT and 21-day second calving rates were significant (Appendix V). For F heifers, there was no relationship between 12- and 15-month LWT and 21-day calving rates for second or third calving, but a curvilinear relationship for first calving 21-day calving rate (Appendix V).

For FJ heifers, 15-month LWT at which maximum first calving 21-day calving rate was estimated to occur was 321 kg (82.3%; Table 6.4), for second calving 21-day calving rate the maximum was estimated to occur at 314 kg (65.2%) and for third calving 21-day calving rate there was no relationship (Table 6.4). Additionally, for 15-month-old FJ heifers, the mean probability of calving within 21 days of first PSC was less than the target of 75% at LWTs less than 231 kg and above 411 kg (Figure 6.1). Likewise, the mean probability of calving within 21 days of second PSC was less than the 60% target at LWTs less than 227 kg and above 401 kg (Figure 6.1). Thereby demonstrating a range in 15-month LWTs where 21-day calving rates were high. Similar results were found for FJ heifers at six and 12 months of age, and other breed groups studied (Appendix V and Table 6.4).

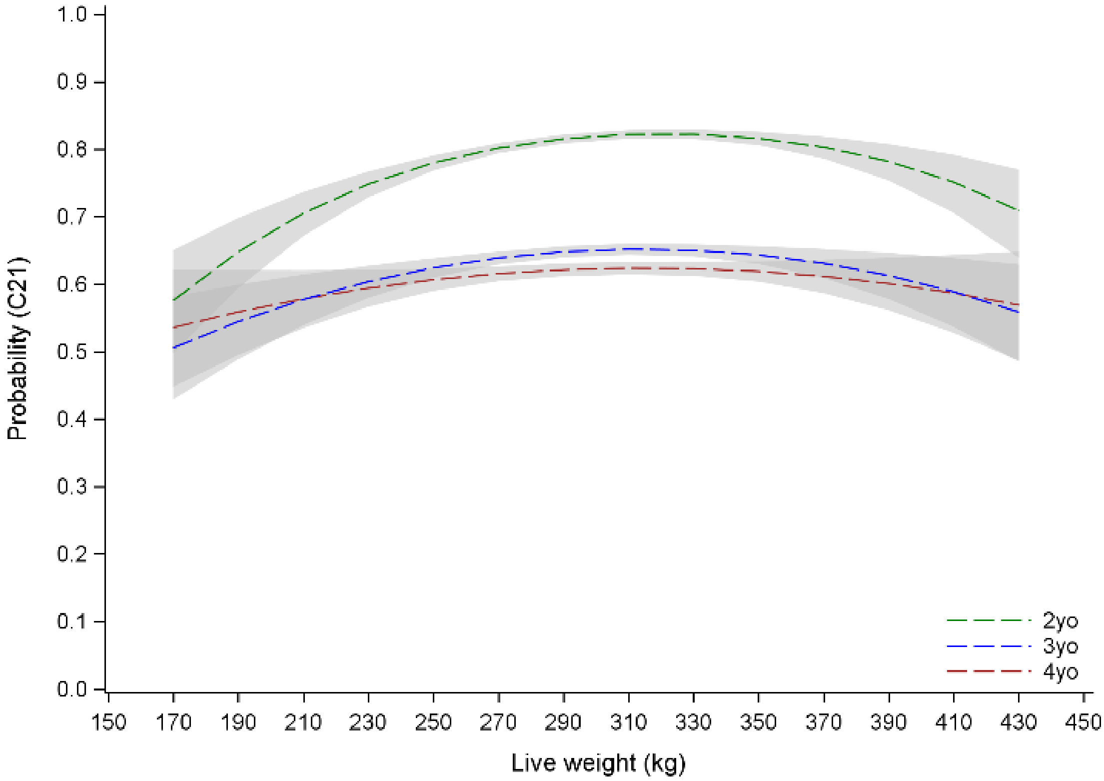

Figure 6.1 Relationship between live weight (LWT) at 15 months of age and calving rate within 21 days of planned start of calving (C21) for Holstein-Friesian-Jersey crossbreed (FJ) heifers that calved that year as two- (2yo), three- (3yo) or four-year-olds (4yo).

Table 6.4 The 15-month live weight (LWT) at which the maximum (max) probability of calving within 21 days of planned start of calving (C21) occurred and the range of LWT where C21 for two-year-old (C21_2yo) heifers was above 75% and three- or four-year-old (C21_3yo, C21_4yo) heifers was above 60%.

Breed group and age		Max	LWT (kg) at max	Range of LWTs (kg) where C21 was:	
F					
	C21_2yo	81.9%	357	above 75%	263 - 451
	C21_3yo	-[1]	-[1]	above 60%	250 - 469
	C21_4yo	-[1]	-[1]	above 60%	-[2]
FX					
	C21_2yo	82.5%	346	above 75%	234 - *NA
	C21_3yo	-[1]	-[1]	above 60%	NA
	C21_4yo	60.8%	322	above 60%	280 - 363
FJ					
	C21_2yo	82.3%	321	above 75%	231 - 411
	C21_3yo	65.2%	314	above 60%	227 - 401
	C21_4yo	-[1]	-[1]	above 60%	239 - 391
JX					
	C21_2yo	81.7%	308	above 75%	201 - 414
	C21_3yo	-[1]	-[1]	above 60%	222 - *NA
	C21_4yo	62.4%	296	above 60%	243 - 350
J					
	C21_2yo	-[1]	-[1]	above 75%	179 - 363
	C21_3yo	-[1]	-[1]	above 60%	NA
	C21_4yo	-[1]	-[1]	above 60%	206 - 294

NA is where C21 was not below 75% for 2yo or below 60% for 3yo or 4yo within the LWT range studied.
[1]Quadratic effect of LWT on C21 was not significant so no maximum was estimated.
[2]No LWT at which probability of C21 was above threshold of 60% for 3yo or 4yo.
Where Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J).

6.4.2.2 Re-calving rate

Similar to LWT effects on calving rate, first calving 21-day re-calving rate was more affected by LWT at six, 12 and 15 months of age compared with second and third 21-day re-calving rates (Appendix V). When significant, the linear effects of LWT were positive and the quadratic effects were negative (Appendix V). For J heifers, there was no age where the relationship between LWT and second calving re-calving rate was significant. Furthermore, there was no relationship between LWT at six months of age and re-calving rate for first, second or third calving J cows (Appendix V).

For FJ heifers, 15-month LWT at which maximum first calving 21-day re-calving rate was estimated to occur was 325 kg (76.9%; **Error! Reference source not found.**), for second calving 21-day re-calving rate the maximum was estimated to occur at 328 kg (55.2%) and for third calving 21-day re-calving rate the maximum was estimated to occur at 315 kg (52.1%; **Error! Reference source not found.**). Additionally, for 15-month-old FJ heifers, the mean probability of re-calving within 21 days of first PSC was less than 70% at LWTs less than 255 kg and above 396 kg (Figure 6.2). Likewise, the mean probability of re-calving within 21 days of second and third PSC was less than 50% at LWTs between 252 kg and 403 kg, and between 253 and 376 kg, for second and third calving, respectively (Figure 6.2). Thereby, demonstrating a range in 15-month LWTs where 21-day re-calving rates were high. Similar results were found for FJ heifers at six and 12 months of age, and other breed groups studied (Appendix V and **Error! Reference source not found.**).

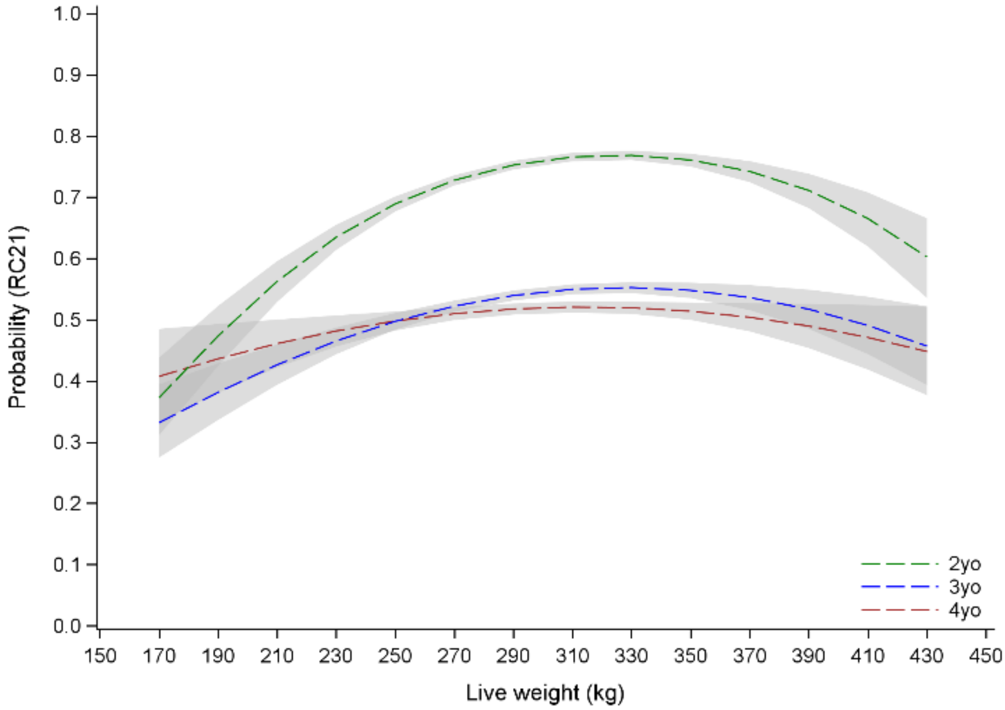

Figure 6.2 Relationship between live weight (LWT) at 15 months of age and re-calving rate within 21 days of planned start of calving (RC21) for Holstein-Friesian-Jersey crossbreed (FJ) heifers that were reared (2yo) or calved the year prior (3yo and 4yo).

Table 6.5 The 15-month live weight (LWT) at which the maximum (max) probability of re-calving within 21 days of planned start of calving (RC21) occurred and the range of LWT where RC21 for two-year-old (RC21_2yo) heifers was above 70% and three- or four-year-old (RC21_3yo, RC21_4yo) heifers was above 50%.

Breed group and age		Max	LWT (kg) at max	Range of LWTs (kg) where RC21 was:	
F					
	RC21_2yo	77.4%	361	above 70%	283 - 439
	RC21_3yo	50.6%	360	above 50%	324 - 395
	RC21_4yo	47.6%	340	above 50%	-[1]
FX					
	RC21_2yo	77.9%	348	above 70%	263 - 432
	RC21_3yo	53.4%	353	above 50%	249 - *NA
	RC21_4yo	50.2%	322	above 50%	304 - 340
FJ					
	RC21_2yo	76.9%	325	above 70%	255 - 396
	RC21_3yo	55.2%	328	above 50%	252 - 403
	RC21_4yo	52.1%	315	above 50%	253 - 376
JX					
	RC21_2yo	75.9%	310	above 70%	240 - 379
	RC21_3yo	53.9%	317	above 50%	246 - 387
	RC21_4yo	51.9%	303	above 50%	256 - 349
J					
	RC21_2yo	72.7%	280	above 70%	228 - 332
	RC21_3yo	-[2]	-[2]	above 50%	232 - *NA
	RC21_4yo	50.9%	266	above 50%	242 - 289

*NA is where RC21 was not below the 'threshold' within the LWT range studied.
[1]No LWT at which probability of RC21 was above 50%.
[2]Quadratic effect of LWT on RC21 was not significant so no maximum was estimated.
Where Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J).

6.4.3 Effects of proportion of 21-month LWT at 12 months of age

6.4.3.1 Calving rate

The relationships between pctLWT21 and 21-day calving rate for first, second and third calving for FJ heifers that were tiny, average or huge in LWT at 21 months of age are displayed in Figure 6.3.

For first calving 21-day calving rate, there was a downward trend, where FJ heifers that were closer their 21-month LWT were less likely to calve early compared with FJ heifers that were further from their 21-month LWT at 12 months of age (Figure 6.3). Whereas, for second and third calving rate, there was no relationship; FJ heifers that were closer to their 21-month LWT at 12 months of age were not more likely to calve early compared with FJ heifers that were further from their 21-month LWT (Figure 6.3). Additionally, heifers that were tiny, average or huge at 21 months of age had similar 21-day calving rates for second and third calving when they were similar in pctLWT21 (Figure 6.3).

Similar relationships were found for the other breed groups studied, and other 21-month LWT categories within each breed group (Appendix V). Due to lower numbers of records at the extremes for pctLWT21, results are presented for heifers that were between 40 and 70% of 21-month LWT at 12 months of age (Figure 6.3).

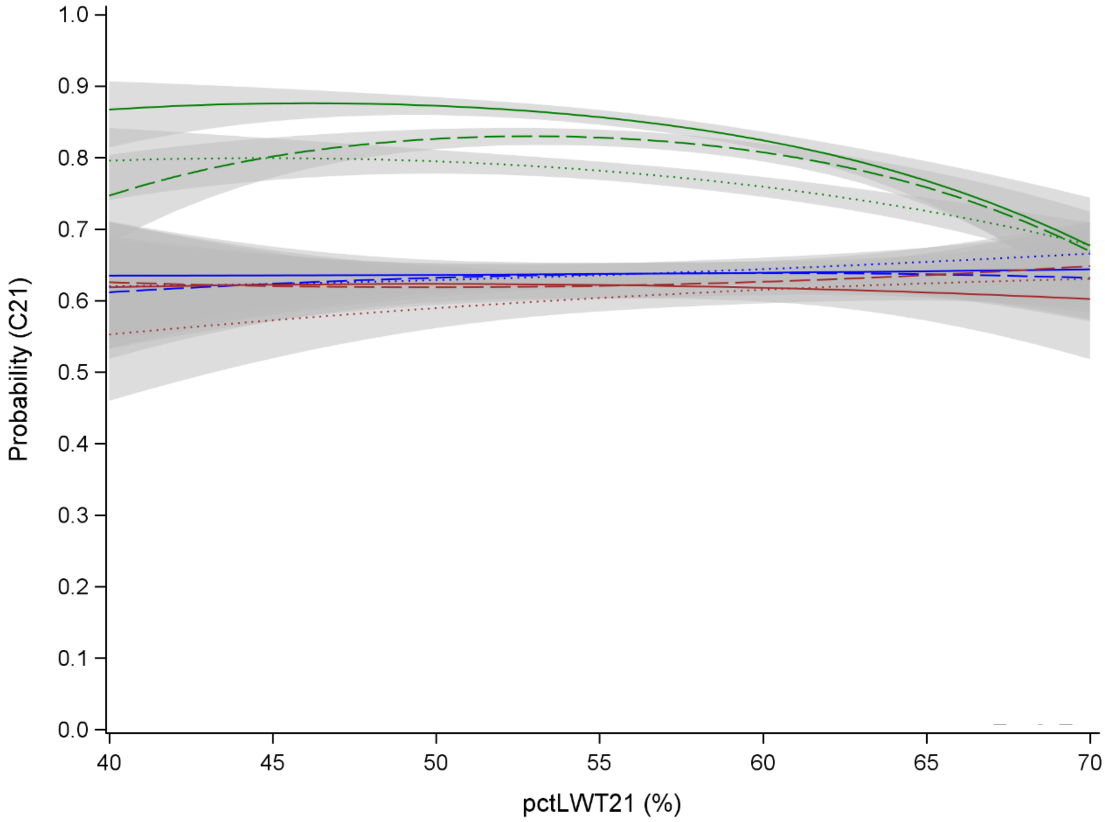

Figure 6.3 Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of calving within 21 days of planned start of calving (C21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Holstein-Friesian-Jersey crossbred (FJ) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.

Results for heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age for 21-day calving rate as two-, three- or four-year-olds are presented in Table 6.6 for heifers that were average in LWT at 21 months of age for their breed group. Results for tiny, small, big and huge heifers within each breed group are presented in Appendix V.

Based on the 95% confidence intervals, within breed group-LWT categories there were small differences in second and third calving 21-day calving rates among heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age (Table 6.6). For first calving 21-day calving rate heifers of all breed groups that were 55% of their 21-month LWT at 12 months of age had greater probability of calving early compared with heifers that were closer (65% pctLWT21) to their 21-month LWT at 12 months of age (Table 6.6). For F, FX, JX and J heifers, those that were 45% of their 21-month LWT at 12 months of age had similar probability of calving early to those that were 55%, both greater than those that were 65% of their 21-month LWT at 12 months of age (Table 6.6). For FJ heifers, that were 45% of their 21-month LWT at 12 months of age had probabilities of calving early similar to that of heifers that were 55 or 65% of their 21-month LWT at 12 months of age (Table 6.6).

For 21-day calving rate for third calving, there were no differences among heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age for any of the five breed groups. For second calving 21-day calving rate, only FX and JX heifers exhibited differences among heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age; all other breed groups had similar 21-day calving rates among heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age (Table 6.6).

Table 6.6 Predicted 21-day calving rate (± SEM) as a two- (C21_2yo), three- (C21_3yo) or four-year-old (C21_4yo) of average 21-month live weight (LWT) heifers that were 45%, 55% or 65% of their 21-month LWT at 12 months of age (pctLWT21).

Breed group and LWT category	Calving rate (%)		
	45% pctLWT21	55% pctLWT21	65% pctLWT21
F			
C21_2yo	$85.1^{b} \pm 1.4$	$82.5^{b} \pm 0.5$	$77.3^{a} \pm 1.0$
C21_3yo	60.1 ± 2.5	59.6 ± 0.8	62.7 ± 1.2
C21_4yo	56.0 ± 3.0	57.8 ± 0.9	59.8 ± 1.4
FX			
C21_2yo	$80.8^{b} \pm 1.3$	$83.4^{b} \pm 0.5$	$75.9^{a} \pm 1.0$
C21_3yo	$57.2^{a} \pm 1.9$	$62.0^{ab} \pm 0.7$	$63.6^{b} \pm 1.2$
C21_4yo	55.7 ± 2.2	60.0 ± 0.8	60.4 ± 1.3
FJ			
C21_2yo	$80.2^{ab} \pm 1.4$	$82.8^{b} \pm 0.6$	$75.8^{a} \pm 1.2$
C21_3yo	61.9 ± 2.1	63.3 ± 0.8	63.3 ± 1.4
C21_4yo	61.4 ± 2.4	61.4 ± 0.9	62.9 ± 1.6
JX			
C21_2yo	$83.8^{b} \pm 1.5$	$82.9^{b} \pm 0.8$	$76.2^{a} \pm 1.5$
C21_3yo	$57.0^{a} \pm 2.5$	$64.3^{b} \pm 1.1$	$63.0^{ab} \pm 1.9$
C21_4yo	55.9 ± 2.9	63.3 ± 1.2	63.2 ± 2.1
J			
C21_2yo	$83.8^{b} \pm 2.5$	$83.1^{b} \pm 1.1$	$72.1^{a} \pm 2$
C21_3yo	58.8 ± 4.5	62.9 ± 1.6	65.0 ± 2.4
C21_4yo	55.2 ± 5.3	62.2 ± 1.8	55.5 ± 2.8

$^{a\text{-}b}$ Values within a row with different superscripts differ at the 95% confidence interval.
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

6.4.3.2 Re-calving rate

The relationships between pctLWT21 and 21-day re-calving rate for first, second and third calving for FJ heifers that were tiny, average or huge in LWT at 21 months of age are displayed in Figure 6.4.

For first calving 21-day re-calving rate, FJ heifers that ended up heavier at 21 months of age (huge vs average vs tiny), had superior re-calving rate at similar pctLWT21 to those that were lighter (Figure 6.4). Additionally, there was a curvilinear relationship between pctLWT21 and re-calving rate (Figure 6.4). For FJ heifers that were average in LWT at 21 months of age, being closer their 21-month LWT (from 40% to 54% pctLWT21) resulted in increases in the probability of re-calving early (Figure 6.4). Similarly, increases in pctLWT21 from 40% to 52% for tiny FJ and from 40% to 51% for huge FJ heifers resulted in increases in the probability of re-calving early (Figure 6.4).

From 54% of 21-month LWT at 12 months of age for average FJ heifers (52% and 51% for tiny and huge, respectively), further increases in pctLWT21 resulted in a decrease in the probability of re-calving early (Figure 6.4). For huge FJ heifers, the rate of decline in the probability of re-calving early was greater than that for tiny FJ. For example, heifers that ended up tiny at 21 months of age but were 60% pctLWT21 had 68.8 ± 0.7% probability of re-calving early, whereas, an increase in pctLWT21 to 65% resulted in a decrease in probability of re-calving of 4.4 percentage units (64.4 ± 0.9%; Figure 6.4). For huge FJ heifers, an increase from 60 to 65% pctLWT21 resulted in a decrease in re-calving rate of 8 percentage units (78.5 ± 0.6% vs 70.5 ± 1.4%, respectively; Figure 6.4).

For second and third re-calving rates, there was little to no relationship between pctLWT21 and re-calving rate (Figure 6.4, Table 6.7 and Appendix V). In general, FJ heifers that were closer to their 21-month LWT at 12 months of age were slightly more likely to re-calve early compared with FJ heifers that were further from their 21-month LWT (Figure 6.4). Additionally, heifers that were tiny, average or huge at 21 months of age had similar 21-day re-calving rates for second and third calving when they were similar in pctLWT21 (Figure 6.4).

Similar relationships were found for the other breed groups studied, and other 21-month LWT categories within each breed group (Appendix V). Due to lower numbers of records at the extremes for pctLWT21, results are presented for heifers that were between 40 and 70% of 21-month LWT at 12 months of age (Figure 6.4).

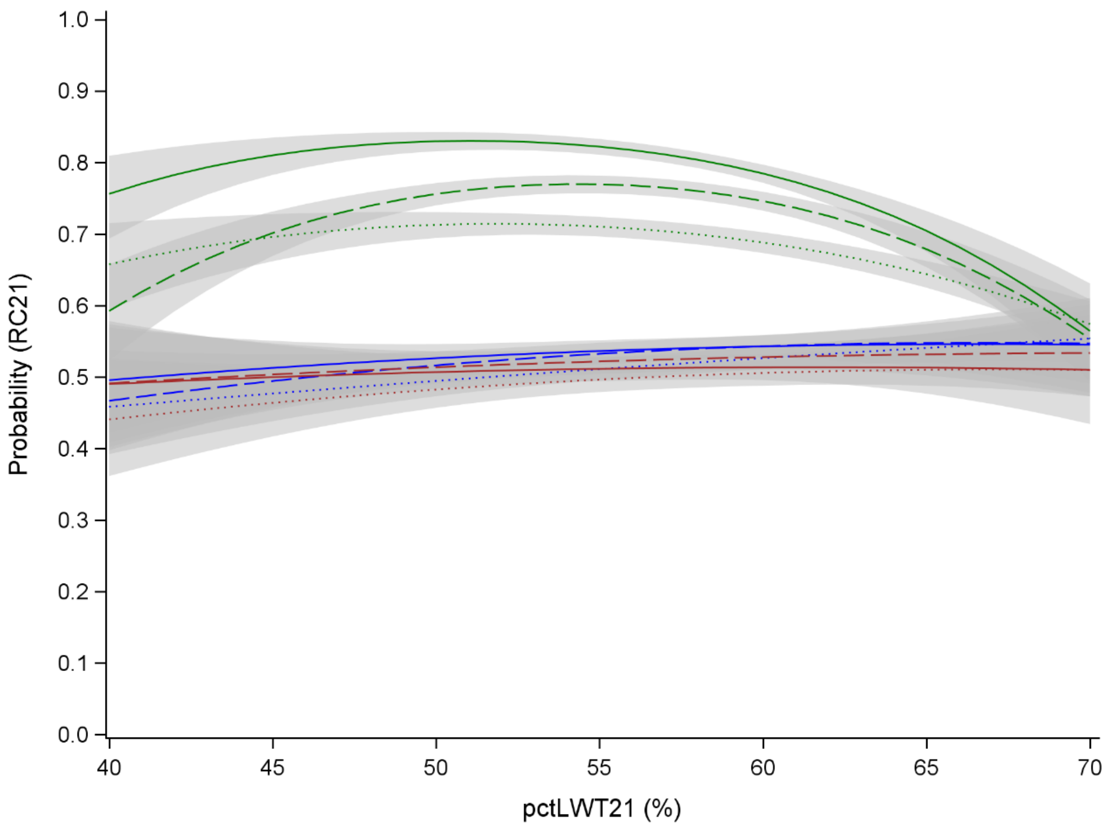

Figure 6.4 Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of re-calving within 21 days of planned start of calving (RC21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Holstein-Friesian-Jersey crossbred (FJ) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.

Results for heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age for 21-day re-calving rate as two-, three- or four-year-olds are presented in Table 6.7 for heifers that were average in LWT at 21 months of age for their breed group. Results for tiny, small, big and huge heifers within each breed group are presented in Appendix V.

Based on the 95% confidence intervals, heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age and were average within breed group were not different in third calving 21-day re-calving rates (Table 6.7). Furthermore, F, FJ and J heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age had similar probabilities of re-calving within 21 days for second calving (Table 6.7). Average JX heifers that were 65% pctLWT21 had a similar probability of re-calving early (53.2 ± 1.8%) to those that were 45% pctLWT21 (45.8 ± 2.2%) and those that were 55% (54.2 ± 1.0%; Table 6.7). Whereas FX heifers that were 65% pctLWT21 had a similar probability of re-calving early (53.4 ± 1.1%) to those that were 55% pctLWT21 (51.3 ± 0.6%), but greater than those that were 45% (46.9 ± 1.7%; Table 6.7).

Results for 21-day re-calving rate were similar to the results for calving rate. First calving heifers of all breed groups that were 55% of LWT21 at 12 months of age had greater probability of re-calving early compared with heifers that were 65% LWT21 (Table 6.7). For F and JX heifers, those that were 45% of LWT21 at 12 months of age had similar probability of re-calving early to those that were 55%, both greater than those that were 65% of LWT21 at 12 months of age (Table 6.7). For FX and FJ heifers, that were 45% of their 21-month LWT at 12 months of age had probabilities of re-calving early similar to that of heifers that were 65% of their 21-month LWT at 12 months of age (Table 6.7). Whereas, for J heifers, those that were 45% pctLWT21 had a similar probability of re-calving early as those that were 55 or 65% pctLWT21 (Table 6.7).

Table 6.7 Predicted 21-day re-calving rate ± SEM as a two- (RC21_2yo), three- (RC21_3yo) or four-year-old (RC21_4yo) of average 21-month LWT heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category	Re-calving rate (%)		
	45% pctLWT21	55% pctLWT21	65% pctLWT21
F			
RC21_2yo	76.6^{b} ± 1.7	77.3^{b} ± 0.6	69.5^{a} ± 1.0
RC21_3yo	46.6 ± 2.3	48.4 ± 0.7	51.8 ± 1.1
RC21_4yo	41.5 ± 2.6	46.2 ± 0.8	47.6 ± 1.3
FX			
RC21_2yo	72.7^{a} ± 1.4	78.0^{b} ± 0.5	68.1^{a} ± 1.0
RC21_3yo	46.9^{a} ± 1.7	51.3^{ab} ± 0.6	53.4^{b} ± 1.1
RC21_4yo	45.2 ± 2.0	49.4 ± 0.7	50.5 ± 1.2
FJ			
RC21_2yo	70.1^{a} ± 1.6	77.0^{b} ± 0.6	67.9^{a} ± 1.3
RC21_3yo	49.0 ± 1.9	52.8 ± 0.8	54.4 ± 1.4
RC21_4yo	49.7 ± 2.2	51.5 ± 0.9	52.5 ± 1.5
JX			
RC21_2yo	76.2^{b} ± 1.7	77.2^{b} ± 0.8	68.1^{a} ± 1.6
RC21_3yo	45.8^{a} ± 2.2	54.2^{b} ± 1.0	53.2^{ab} ± 1.8
RC21_4yo	45.4 ± 2.6	52.2 ± 1.2	51.7 ± 2.0
J			
RC21_2yo	73.8^{ab} ± 3.1	76.5^{b} ± 1.2	67.1^{a} ± 2.0
RC21_3yo	42.4 ± 3.8	51.6 ± 1.5	53.0 ± 2.2
RC21_4yo	46.2 ± 4.9	51.7 ± 1.7	47.4 ± 2.6

$^{a\text{-}b}$Values within a row with different superscripts differ at the 95% confidence interval.

F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

6.5 Discussion

The aims of this study were to explore the relationships between LWT of dairy heifers and reproduction and between pctLWT21 and reproduction for first, second and third calving. Results reported here showed that there were significant impacts of LWT at six, 12 and 15 months of age and pctLWT21 on the reproductive variables calving rate and re-calving rate. The analysis of reproductive variables is difficult, especially when considering variables such as calving interval, days to calving and calving rate, as females that did not calve are treated as missing in the dataset. Treating females that did not calve as missing (i.e. C21) does not consider an important source of variation in fertility (Donoghue et al. 2004), in that females that failed to calve at all also failed to calve within 21 days. The current study has considered LWT and pctLWT21 effects on both calving rate (including only cows that calved; C21) and re-calving rate (including cows that were old enough to calve but failed to do so, hence also failed to calve early; RC21) in order to provide a thorough analysis of calving pattern.

Results from Chapter 5 showed that heifers at both extremes of LWT were less likely to calve each year compared with heifers in the mid-range of LWT for their breed group. Unsurprisingly, due to the inclusion of heifers that failed to calve in the re-calving rate dataset of the current study, there was a greater effect of LWT on re-calving rate compared with calving rate; as it was a combination of stayability from the previous year and calving early in the current year for those that did calve. Nevertheless, there was a large range in LWT where C21 and RC21 were "good" and this range overlapped. The target C21 for first calving heifers is 75% (DairyNZ 2018c), and FJ heifers that were between 231 and 411 kg at 15 months of age had a predicted mean 21-day calving rate of 75% or greater. To the author's knowledge there are no targets for either three-week in-calf rates of 15-month heifers, or for re-calving rates. For the purposes of this study an arbitrary target of 70% was used. The range in 15-month LWT of FJ heifers where re-calving rate exceeded 70% was between 255 and 396 kg. The mean 15-month LWT of FJ heifers was 301.5 kg (Chapter 3), indicating that there was a large range (141 kg) in 15-month LWT (46.5 kg below average and 94.5 kg above average) where first calving pattern was good. The industry target LWT at 15 months of age is 60% of mature LWT (DairyNZ 2015a; Troccon 1993). Based on the weighted average of Holstein-Friesian-Jersey crossbred cows at maturity (between five and eight years of age) of 480.8 kg (Livestock Improvement Corporation & DairyNZ 2018), the average target LWT would be 288.5 kg for 15-month-old FJ heifers. This estimated target is within the range identified for "good" calving pattern for FJ heifers, although it is at the lower end of the LWT range.

Irish Holstein-Friesian heifers that were heavier at mating calved earlier than heifers that were lighter at mating (Archbold et al. 2012). The relationship appeared to be curvilinear, as the lightest heifers (≤290 kg) calved 16, 14 and 10 days later than the heaviest (≥343 kg), and two mid-range groups (317-342 and 291-316 kg), respectively (Archbold et al. 2012). Similarly, McNaughton and Lopdell (2013) found a significant curvilinear relationship between target LWT at PSM and calving date relative to PSC, in that heifers that were further from target LWT (below and above) calved later compared with heifers that were closer to target LWT. Results from the current study supported those from Archbold et al. (2012) and McNaughton and Lopdell (2013) in that lighter heifers calved later than heifers that were in the mid-range for LWT and the relationship was curvilinear; with heifers at the heaviest end of the LWTs included in the current study being less likely to calve within 21 days of PSC compared with heifers that were in the mid-range for their breed group. Despite this, the lightest heifers had inferior reproductive performance compared with the heaviest heifers, therefore, being "too light" was worse for C21 and RC21 compared with being "too heavy".

The target for the whole herd is 60% of cows calved within 21 days of PSC (DairyNZ 2018c), this is inclusive of first calving heifers, that as mentioned previously, tend to calve earlier than the rest of the herd. There is currently no C21 target that excludes first calving heifers, therefore, the 60% calved within 21 days is the closest target calving rate available for second and third calvers. To the author's knowledge there are no targets for three-week re-calving rates, therefore, for the purposes of this study an arbitrary target of 50% was used as a threshold for "good" re-calving rate of second and third calvers. There were small effects of heifer LWT on second and third 21-day calving and re-calving rates. Similar to first calving, the effect of LWT was greater on re-calving rate compared with calving rate. Twenty-one-day calving rate includes only the animals that calved that year, whereas, RC21 includes animals that failed to calve early that year for reasons other than calving late such as failure to conceive or being culled for low milk production. Results from Chapter 3 showed that heifers that were light for their breed group had lower milk yields in first lactation compared with heifers that were heavier. Furthermore, heifers that that were light for their breed group were less likely to remain in the herd to calve a second time compared with heifers that were heavier (Chapter 5). Possibly, the lighter heifers were removed from the herd prior to second calving due to low milk production in first lactation, hence why the effect of LWT on re-calving rate was greater than on calving rate. For FX, J and JX heifers, there was no relationship between LWT and 21-day calving rates for second calving for any age studied; whereas for re-calving rate, only J heifers displayed no relationship between LWT and calving or re-calving rate.

As with the analyses for stayability and marginal stayability in Chapter 5, the deviation from median date of birth and median date of calving the year prior were included as covariates in the analyses for calving and re-calving rates in order to estimate the effect of LWT or pctLWT21 on the calving in question, without the effect of date of birth (or calving). Based on the results reported by Jenkins et al. (2016) and Pryce et al. (2007), it was hypothesised that being born earlier in the calving period may provide a fertility advantage to heifers at their first calving, which may have carryover advantages on second and third calving. There was a small but significant effect (~0.10% per day earlier) of date of birth on probability of calving or re-calving early in first or second calving, additionally, there were smaller effects (~0.05% per day earlier) of date of birth on calving or re-calving early in third calving. Removal of date of birth from the analyses (LWT and pctLWT21) made little difference to the models (data not shown), indicating that the benefits of increased premating LWT on 21-day calving and re-calving rates existed regardless of how early or late the heifer was born. Additionally, the effect of date of first calving was significant and negative, for each day later the animal calved, there was a 0.35% lower probability of calving or re-calving within 21 days of PSC for second calving. Likewise, for third calving analyses (LWT and pctLWT21), the effect of date of second calving was significant and negative at 0.55% lower probability of calving or re-calving early for each day later the animal calved at second calving. Despite this, removing date of previous calving from the analysis made little difference to the models (data not shown), indicating that the relationship between premating LWT on calving and re-calving rates existed regardless of how early or late the cow calved the year prior. In addition, Archbold et al. (2012) reported that calving date of heavier heifers was not different to that of lighter heifers in second or third lactations. These results indicated that although there were benefits to earliness of first calving of increased premating LWT, these benefits were not as pronounced for C21 in second and third calvings, and perhaps other factors (such as oestrus detection and nutrition during lactation) were having a greater impact on reproduction in subsequent lactations.

Heifers that were in the heaviest range of pctLWT21 (>65%) within breed group-LWT category were less likely to calve or re-calve early compared with heifers in the mid-range of pctLWT21 within the same breed group-LWT category. Differences in oocyte quality were reported in a study of Scottish dairy x beef heifers of low or moderate body condition score (BCS) that were fed either once or twice maintenance requirements (Adamiak et al. 2005). Heifers of low BCS benefitted from a high level of feeding, whereas, a high level of feeding to heifers of moderate BCS was detrimental to oocyte quality (Adamiak et al. 2005). As mentioned in Chapter 5, BCS records were not available for heifers in the current study. It is likely that two heifers that were similar in LWT at 21 months of age but differed in LWT at 12 months of age would also differ in BCS at 12 months of age, due to the positive correlation between LWT and BCS (Roche et al. 2007). For example, heifers that were closer to their 21-month LWT at 12 months of age may have been in greater condition compared with heifers within the same breed group-LWT category that were further from their 21-month LWT at 12 months of age. Heifers in the current study on average grew faster from 12 to 20 months of age than they did between five and 12 months of age (Chapter 2), likely due to increased pasture quality and quantity that occurs during spring when heifers are between 14 and 17 months of age. As suggested by Adamiak et al. (2005), the fast growth rates over the breeding period (12 to 18 months of age) may have been detrimental to the heifers that were of greater BCS (greater pctLWT21 within breed group-LWT category), whereas, the fast growth rates over the breeding period may have been beneficial to the heifers that were of lower BCS (lesser pctLWT21 within the same breed group-LWT category). The study by Adamiak et al. (2005) was of heifers fed a concentrate-based diet, and the authors postulated that a possible mechanism for the reduction in oocyte quality was due to a high level of concentrate feeding to the moderately fat heifers causing hyperinsulinemia. Therefore, application of the results from Adamiak et al. (2005) to heifers in pasture-based systems should be treated with caution due to differences in dietary composition between the systems.

Heifers that were a low proportion of their 21-month LWT at 12 months of age would have done a larger proportion of their growing in their second year (12 to 21 months of age) compared with their first year. In contrast, heifers that were a greater proportion of their 21-month LWT at 12 months of age would have done a larger proportion of growing in their first year compared with their second year. As previously mentioned, heifers in the current study grew faster from 12 to 20 months of age than they did between five and 12 months of age (Chapter 2). Despite this, heifers that were a greater pctLWT21, grew faster up to 12 months of age and slower between 12 and 21 months of age than heifers that were a lesser pctLWT21 (Chapter 4). For example, average FJ heifers that were 45% pctLWT21 grew at 0.42 kg/d from nine to 12 months of age, whereas, heifers that were 65% pctLWT21 grew at 0.60 kg/d over the same period. From 12 to 15 months of age, average FJ heifers that were 45% pctLWT21 grew at 0.78 kg/d, whereas, heifers that were 65% pctLWT21 grew at 0.66 kg/d over the same period. From 15 to 18 months of age, the growth rates were 0.99 kg/d and 0.61 kg/d for 45 and 65% pctLWT21, respectively. Although the absolute values for growth rates of tiny and small FJ heifers were less than that of average FJ heifers, the same pattern of faster growth over the breeding period (12 to 18 months of age) of heifers that were 45% pctLWT21 compared with heifers that were 65% existed (Appendix III). Likewise, for big and huge FJ heifers, those that were 45% pctLWT21 grew faster over the breeding period than those that were 65% pctLWT21 within breed group-LWT category (Appendix III). The comparatively faster growth over the breeding period of the heifers that were 45% pctLWT21 may have been beneficial to their breeding performance.

Two studies comparing plane of nutrition of dairy heifers concluded that there was no impact on reproduction of differing planes of nutrition (Ducker et al. 1982; Macdonald et al. 2005). However, Ducker et al. (1982) reported that within each plane of nutrition group, there were differences in pregnancy rate; heifers with the most severe response to the change from a high to a low plane of nutrition (lost the most BCS/LWT), were less likely to conceive than those within the same treatment that were better able to maintain BCS/LWT. Likewise, heifers that had a greater increase in BCS/LWT when switched from a low to a high plane of nutrition were more likely to conceive than heifers that did not have as a great a response to a change in nutrition. The results from Ducker et al. (1982) were similar to that reported for the current study. Nevertheless, both Ducker et al. (1982) and Macdonald et al. (2005) synchronised the oestrus of heifers before mating, potentially masking any nutritional related differences in cycling. It is not known what proportion of heifers included in the current study had their oestrus synchronised, however, based on the number of dairy cattle in New Zealand (n=4,861,324) and an approximate 20% replacement rate, there are close to one million dairy heifers reared per year (Livestock Improvement Corporation & DairyNZ 2017). For the 2016/17 season, 177,170 heifers were recorded as mated to artificial insemination (approximately 18% of one million), hence, may have had oestrus synchronised; thereby indicating that the proportion synchronised in the current dataset would be low and therefore, have small effects on the results presented here.

The recommended target LWTs for New Zealand dairy heifers are 30% of mature LWT at six months of age, 60% at 15 months of age and 90% pre-calving (DairyNZ 2015a; Troccon 1993). As discussed previously in Chapter 5, heifers that attained target LWT at 12 (50% mature LWT) and 21 months of age (86% mature LWT) would have been 58% of their 21-month LWT at 12 months of age. Results from the current study indicated that heifers that were between 45 and 55% of their 21-month LWT at 12 months of age had better calving and re-calving rates than heifers grown to be greater proportions of their 21-month LWT. Therefore, results from the current study indicate that heifers that were slightly below target at 12 months of age had better calving and re-calving rates compared with heifers that exceeded target at 12 months of age but met 21-month target LWT. As mentioned earlier, this may be due to the faster growth rates over the mating period for heifers that were a lower proportion of 21-month LWT compared with heifers that were a greater proportion of 21-month LWT. A study that used LWT breeding values to estimate mature LWT and hence proportion of target LWT achieved, showed that only 12% New Zealand dairy heifers were above target LWT at 12 months of age, whereas 66.5% were below target at the same age (Handcock et al. 2016). In the same study, 25.8% of heifers were on target at 22 months of age (Handcock et al. 2016), however, it was not reported what percentage of heifers that were on target at 22 months of age were also on target (or below target) at 12 months of age.

It is well reported that milk production and reproduction are genetically correlated (Berry et al. 2003; Grosshans et al. 1997), in that the selection of cattle to produce more milk is associated with reduced fertility. The phenotypic correlations between milk production and fertility are close to zero (Grosshans et al. 1997), hence it is possible through management practices to reduce the negative effects on reproduction of high milk production. Despite this, the majority of cows enter a state of negative energy balance after calving, high-yielding cows have better abilities to mobilise fat and muscle to support high milk production and hence are more likely to be in a more severe negative energy balance compared with a lower yielding cow (Wathes et al. 2007). In addition, cows that have higher BCS at calving have more BCS available to mobilise and are also likely to be in a more severe negative energy balance. A New Zealand study by Roche et al. (2007) demonstrated that there was a curvilinear relationship between BCS at mating and the probability of exhibiting oestrus before mating; with a BCS of 5.5 having the greatest probability and cows that had BCS higher or lower than 5.5 having a decreased probability of exhibiting oestrus. In addition, all of the reproductive measures studied (probability of exhibiting oestrus before PSM, being mated within 21 days of PSM, pregnant to first mating, or within 21, 42, and 84 days of PSM) were negatively affected when LWT or BCS during lactation indicated a more severe or longer duration of the negative energy balance after calving. Cows that lost more BCS or LWT from calving to mating start date, were less likely to exhibit oestrus before mating start date compared with cows that did not lose as much BCS or LWT (Roche et al. 2007). This more severe negative energy balance is associated with reduced fertility (Wathes et al. 2007), which may in part explain the reduced reproductive performance observed in the heaviest heifers in the current study. Further research is necessary to identify why the heaviest heifers had poorer calving and re-calving rates compared with the heifers in the mid-range for LWT.

Breed groups differed in reproductive performance, with crossbreeds (FX, FJ and JX heifers) generally having better performance compared with straight breeds (F and J heifers). These results are in agreement with those of Xu and Burton (2003) who reported that crossbred cows have approximately 2% greater six-week in-calf rate compared with F and J cows. In addition, both F and J breed groups were similar in 21-day calving rate for first calving. Twenty-one-day calving, and re-calving rates were superior for J cows compared with F cows for second and third calvings. These results are similar to that reported by Grosshans et al. (1997), where first and second lactation J cows had better reproductive performance (shorter intervals from PSM to first service and conception, fewer days open, shorter calving interval and greater proportions conceiving within 21 and 42 days of PSM) compared with F cows. In addition, Xu and Burton (1999) reported that 15-month-old Friesian heifers had higher conception rates and pregnancy rates and lower nonpregnancy rates compared with Jersey heifers, and MacMillan (1994) reported that the nonpregnancy rate for F heifers was 5.4% compared to 10% for J heifers. Results from the current study and that reported in Chapter 5 support those of Xu and Burton (1999), MacMillan (1994) and Grosshans et al. (1997), where F heifers were more likely to calve than J heifers, whereas, the reproductive performance of J cows exceeded that of F cows for second and third calving.

6.6 Conclusion

There were positive curvilinear relationships between premating LWT and reproductive performance of dairy heifers. Heifers that were heavier at six, 12 and 15 months of age were more likely to calve early for first calving compared with heifers that were lighter, regardless of breed group. Despite this, heifers that were further from their 21-month LWT at 12 months of age that did calve, were more likely to calve early in first lactation compared with heifers that were closer to their 21-month LWT at 12 months of age. When heifers that did not calve were included as also failing to calve early, heifers that were in the mid-range for pctLWT21 had the greatest probability of calving early in first lactation. For second and third lactations however, the impacts of heifer premating LWTs or pctLWT21 on the earliness of calving were small. For heifers that were at the heaviest end of the LWT range and heifers that did the greatest proportion of growing in their first year of life in the current study, there was a slight decline in reproductive performance compared with heifers in the mid-range of LWT. Consequently, for heifers that were below average in LWT, there would be considerable reproductive benefits over the first three calvings by improving rearing practices to result in heavier heifers throughout the premating rearing phase.

Foreword to Chapter 7

The results presented in Chapters 2 to 6 were from the retrospective analysis of a large dataset. These studies indicated that growth prior to first calving, in particular, up to 12 months of age is important to milk production, stayability and reproductive variables. The dataset used for Chapters 2 to 6 did not include records on age or LWT at puberty, body condition score (BCS) or stature/frame size and had few records on early-aged pregnancy diagnosis. In addition, as these were retrospective studies, the results presented were associations and not necessarily causations. It was therefore valuable to test prospectively the effects of growth trajectory prior to first calving on the milk production of New Zealand dairy heifers to complement the retrospective analyses from previous chapters. The experiment presented in Chapter 7 was designed to use differential feeding to generate two distinct growth trajectories (linear vs seasonal) and to determine if the differing growth trajectories resulted in differences in frame size, age at puberty or milk production, LWT or BCS in first lactation.

Chapter 7 Linear versus seasonal growth of dairy heifers decreased age at puberty but did not affect first lactation milk production

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7.1 Abstract

The aim of this study was to compare conformation, age at puberty and subsequent milk production of Holstein-Friesian-Jersey crossbred heifers grown in a linear trajectory (Target; n=55) between six- and 15-month target liveweights (LWT), with heifers grown in a seasonal manner (Seasonal; n=55) of slow over first winter and fast over spring. Heifers that grew to Target attained puberty 38 days earlier than heifers that grew in a seasonal manner; however, no difference between treatments in date of first calving occurred. Heifers in the seasonal treatment were 1 cm (P=0.032) taller than those in the target treatment, but similar in girth and length. There was no effect of treatment on first lactation milk production. These results suggest that provided heifers reached their premating target LWT, the growth trajectory between target LWT at six and 15 months of age did not negatively impact frame size or first lactation milk production.

7.2 Introduction

Two of the most important periods in heifer rearing in terms of reproductive performance and milk production are mating and pre-calving. Puberty in heifers occurs at approximately 45 to 50% of mature liveweight (LWT) (Garcia-Muniz et al. 1998; McNaughton et al. 2002). To ensure that heifers have attained puberty before planned start of mating (PSM), the target LWT is 60% of mature LWT (Burke et al. 2007; Troccon 1993). More heifers that were bred to their third oestrus were pregnant (78%) compared with heifers that were bred to their first oestrus (57%), indicating that fertility improved over the first few oestrous cycles (Byerley et al. 1987). Therefore, it is advantageous to have all heifers pubertal before the PSM.

Several studies have shown that heifers that were heavier (Macdonald et al. 2005; van der Waaij et al. 1997) or closer to target LWT (McNaughton & Lopdell 2013) before first calving had greater first-lactation milk production than did lighter heifers.

Target LWTs for dairy heifers were developed by Troccon (1993) in France and were recommended for use in New Zealand by Penno (1997). Industry target LWTs for dairy heifers are 30% of mature LWT at six months of age, 60% at PSM (15 months of age) and 90% pre-calving (22 months of age) (Burke et al. 2007; Troccon 1993). Target growth rates are calculated by linear interpolation, thereby creating a mostly linear trajectory of growth from six to 15 and 15 to 22 months of age.

In the pasture-based farming systems in New Zealand, dairy heifers tend to follow a seasonal pattern of growth that matches pasture quality and availability (Handcock et al. 2016; Litherland et al. 2002; McNaughton & Lopdell 2012), rather than a linear growth trajectory. In the analysis by McNaughton and Lopdell (2012), heifers during their first autumn/winter (nine - 12 months of age) had very low growth rates (0.32 kg/d), compared with a target of 0.55 kg/d. However, over the following spring period (12 – 15 months of age) heifers grew faster (0.65 kg/d) than in the winter period, but were not able to regain target trajectory. A subsequent study (Handcock et al. 2016) indicated that heifer growth had improved since the study by (McNaughton & Lopdell 2012), however, heifers were still growing in a seasonal pattern of slow over winter and fast over spring. It is not known what effect different growth rates between the target LWTs have on future milk production and reproductive performance in New Zealand dairy heifers.

The aim of this experiment was to use differential feeding to generate LWT profiles (linear trajectory between target LWT at six and 15 months of age vs a seasonal trajectory, similar to industry norms) and determine if the differing LWT profiles resulted in differences in frame size, age at puberty or in subsequent milk production, LWT or BCS of heifers in first lactation. In addition, binary data on first pregnancy and rebreeding performance was recorded. It was hypothesised that the differing LWT profiles would result in differences in age at puberty, but there would be no difference in milk production between dairy heifers grown in a seasonal or linear growth pattern.

7.3 Materials and methods

This experiment was completed at Massey University's Keeble and No. 4 Dairy Farms near Palmerston North, New Zealand, with approval from the Massey University Animal Ethics Committee (MUAEC 15/107).

7.3.1 Animals

One hundred and ten Holstein-Friesian-Jersey crossbred heifers were selected for this experiment. Heifers were replacements for Massey University's No. 4 Dairy Farm born in the spring of 2015 on either No. 1 or No. 4 Dairy Farms, with a median birthdate of the 8th August (range 17/07/2015 – 31/08/2015). All animals were DNA verified to sire and dam.

7.3.2 Treatments

At six months of age, heifers were allocated to one of two treatments; "Target" (n = 55) or "Seasonal" (n = 55). The Target treatment consisted of heifers achieving a consistent rate of growth (0.6 kg/day) from target LWT at six months of age to target LWT at 15 months of age (planned start of first mating; PSM1); the Seasonal treatment consisted of heifers achieving a slow rate of growth (0.4 kg/day) from six to 12 months of age, followed by a rapid rate of growth (0.9 kg/day) until PSM1, so that both treatments achieved 60% of estimated mature LWT at PSM1.

To calculate target LWT a standard birthdate (26/07/2015) that was the planned start of calving (PSC) the year the heifers were born in was applied to all heifers (Handcock et al. 2016; McNaughton & Lopdell 2013). The expected mature LWT of the heifers was calculated as 524 kg (500 kg + average LWT breeding value (BV) of the heifers; 24 kg) (DairyNZ 2015a). Target LWT was calculated as 30%, 60% and 90% of expected mature LWT at six, PSM1 and 22 months of age. Linear interpolation between the three targets was used to calculate targets at intermediate ages. A heifer was considered to have reached target LWT if her LWT was equal to or greater than the target. The percentage of target LWT achieved was calculated by dividing the heifer's actual LWT by the target LWT.

The experimental period was from the 2nd February (six months of age) until 12th October 2016 (PSM1). Heifers were allocated to treatments balanced for date of birth, LWT (seven days prior to the start of the experiment), previous growth rate (from 21 to seven days prior to the start of the experiment), grazing herd prior to the start of the experiment (n=3), Friesian breed proportion, LWT BV and Breeding Worth (BW) from the 08/01/2016 Animal Evaluation run. Other BVs and ancestry were also checked to be balanced between treatments, with priority to LWT being balanced between treatments.

During the experimental period, heifers were located at Massey University's Keeble farm. They were grazed in their treatment groups and allocated ryegrass/white clover pasture based on fortnightly LWT measurements and the growth rate required. Heifers were supplemented with meal, pasture baleage and/or Winfred rape (*Brassica napus)* when pasture quality/availability was not sufficient to meet the growth rate required.

The timeline of the experiment is depicted diagrammatically in Figure 7.1.

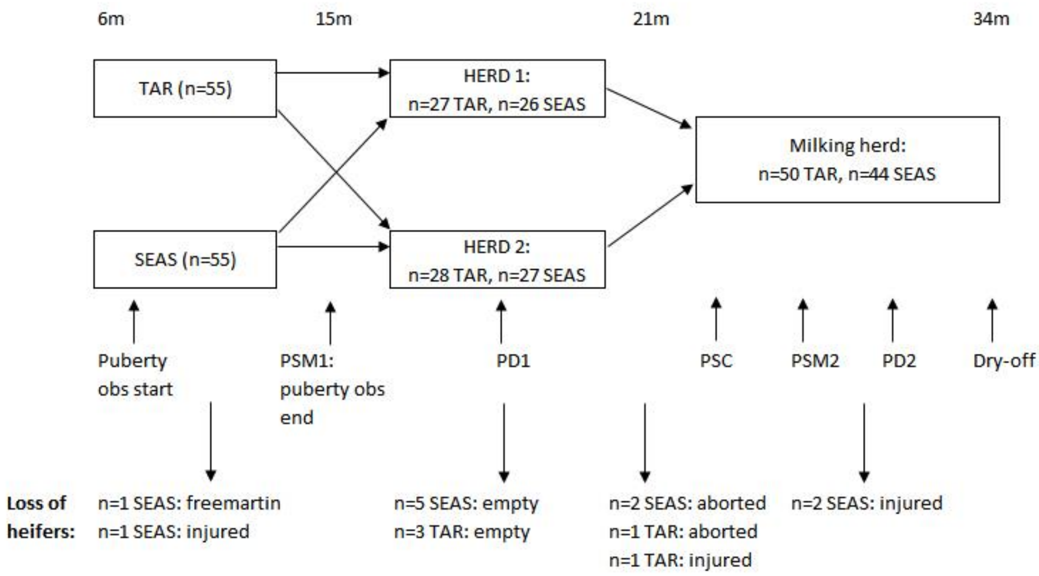

Figure 7.1 Diagrammatic representation of the experimental timeline and number (n) of heifers grown to Target (TAR) or in a Seasonal pattern (SEAS) from six months of age to mating at 15 months of age and follow-up observations until end of first lactation (dry-off). Where obs is observations; PSM1 and PSM2 are planned start of first and second mating, respectively; PD1 and PD2 are pregnancy diagnosis for first and second pregnancy, respectively; PSC is planned start of calving.

7.3.3 Post-trial animal management

From PSM1 until May 2017 heifers were allocated to one of two herds balanced for treatment and percentage of target liveweight achieved at PSM1 for management purposes. During which time they continued to graze at Massey University's Keeble farm. Jersey bulls (n = 4 per herd; ratio 4:55) were used for 53 days of natural mating, from the 14th October 2016 until 6th December 2016.

From May 2017 pregnant heifers were returned to Dairy 4 for their first calving and were managed as one herd with the three-year-old cows until calving. After calving, heifers were milked twice daily until the 22nd November 2017 when they switched to once-a-day until dry-off in May 2018.

Heifers were managed as a commercial herd, BCS was monitored monthly on a 1-10 scale (Roche et al. 2007), and heifers with low BCS (≤3.5) in August were managed as a separate herd with an increased feed allowance until 29th September 2017 when they returned to the herd.

7.3.4 Measurements

7.3.4.1 Liveweight and conformation measurements

Unfasted LWT was recorded fortnightly from six until 10 months of age and weekly from 10 until 15 months of age. From 15 months of age until calving, LWT was recorded monthly. Post-calving, heifers were weighed daily after milking using a walk-over-weigh system (WOW! XR-3000®, Tru-Test, Auckland, New Zealand). Body condition score was assessed at 15 and 24 months of age, and 10 times during first lactation. At each time point, a single assessor assessed all heifers, allowing comparisons between groups on each day. During lactation, BCS was assessed by the same person throughout.

Conformation measurements (wither height, crown-to-rump-length and girth) were recorded at six, 12, 15 and 21 months of age. Wither height was measured using an adjustable height stick and was recorded as the vertical distance between the ground to the top of the heifer's wither (Handcock et al. 2015; Macdonald et al. 2007). Crown-to-rump length was taken from the crown along the spine to the base of the tail and girth measurements were taken behind the 13th rib, both using a flexible tape measure (Handcock et al. 2015). At 15 and 21 months of age the length along the spine from the base of the tail to withers was measured using a flexible tape measure (Macdonald et al. 2007).

7.3.4.2 Puberty measurements

KAMAR® Heatmount Detectors were applied on the 16th March 2016 (approximately 7.5 months of age) to identify behavioural oestrus. Heifers were observed weekly to detect activated KAMARS, which were recorded as activated or missing and replaced as necessary. The ovaries of heifers that had an activated or missing KAMAR® were scanned using transrectal ultrasonography (DP6600; Mindray, Sichuan, China) with a 7.5-mHz probe and a fixed inducer seven days after activation, to detect the presence of a corpus luteum (CL). Oestrus was defined to have occurred when a KAMAR® was activated or missing, followed seven days later by an observable corpus luteum. Puberty was defined as two consecutive oestrus events, within 28 days of one another indicating regular cyclic ovarian activity. The first oestrus event was defined as the date of "puberty". Once a heifer attained puberty, or at PSM1, whichever came first, oestrus events were no longer observed for that heifer. In addition, heifers that were confirmed to have conceived within 28 days of a heifers' first oestrus were considered as pubertal at that first oestrus event.

Seven days prior to the PSM1, all heifers that had not attained puberty were scanned for the presence of a CL. If no CL was present, they were rescanned at PSM1 to identify those that had been in the follicular phase of their cycle at the first scan. If there was no CL detected at either of those two scans, the heifer was considered to be pre-pubertal at PSM1. Heifers with one CL detected before PSM1 were also considered to be pre-pubertal at PSM1 because they had not had an observed oestrus event.

Birth dates of the heifers were used to calculate "age at puberty", for all other measurements the standard birthdate (26/07/2015) for heifers was used. Estimated number of oestrous cycles pre-mating were calculated as follows; heifers with a date of puberty on or before 17/08/2016 (63 days before PSM1) were estimated to have had three or more oestrous cycles before PSM1, heifers with a date of puberty on or before 07/09/2016 (42 days before PSM1) were estimated to have had two oestrous cycles before PSM1, heifers with a date of puberty before 28/09/2016 (21 days before PSM1) were estimated to have had one oestrous cycle before PSM1. All other heifers were given a value of zero for estimated number of oestrous cycles.

7.3.4.3 Pregnancy scanning

Pregnancy scanning was performed on 17th January 2017 (18 months of age) to identify heifers that had conceived during the first cycle (1-21 days), second cycle (22-42 days) or later (43-53) of mating. A date of conception could not be determined for two heifers (n=1 Seasonal and n=1 Target) as they were in the process of aborting at pregnancy diagnosis. For analysis, these two heifers were considered to have conceived during the mating period; but were treated as missing values for the analysis of cycle of conception.

Pregnancy status was determined by transrectal ultrasonography using the same equipment described for the pubertal ovarian ultrasonography. Heifers that were not pregnant (or were aborting) were removed from the experimental herd at pregnancy diagnosis and excluded from subsequent measurements (Figure 7.1).

7.3.4.4 Calving and dry-off dates

Calving and dry-off dates were recorded for each heifer in MINDApro™ (LIC Corporation Limited, Hamilton, New Zealand). Days lactating was calculated as the difference between calving and dry-off dates or if a heifer died or was culled, the difference between calving and date of death or sale were used.

7.3.4.5 Milk production and milk composition

Heifers were herd tested approximately monthly (six times) during lactation. Total lactation yields (milk yield, protein yield and fat yield) were extracted from MINDApro™ at completion of lactation. Herd-test records for somatic cell count (SCC) were also extracted to calculate somatic cell score (SCS) using SCS = log2 (SCC).

7.3.4.6 Reproductive performance during first lactation

Pre-mating heats were detected using tail paint from 15th September 2017 until 18th October 2017 (PSM2). Any heifer that had calved prior to the 30th August 2017 and had not been identified in oestrus by the 3rd October 2017 was treated with prostaglandin. Following prostaglandin treatment, any heifers that were not identified in oestrus by the 10th October 2017 were treated for anoestrus using a controlled internal drug releasing device (CIDR).

Artificial insemination was used for nine weeks during the heifers' second mating, starting on the 18th October 2017 and ending on the 24th December 2017.

Three and six-week in-calf rates were calculated as:

$$\frac{\#\ cows\ pregnant\ in\ three\ (or\ six)\ weeks}{total\ \#\ cows\ at\ PSM} \times 100$$

(Burke et al. 2007).

7.3.4.7 Culling reasons and times

Heifers were removed throughout the duration of the experiment as depicted in Figure 7.1.

7.3.5 Data handling

Similar to using herd test data to generate a daily milk profile, all available LWT data during rearing were used to generate a daily LWT profile from six to 21 months of age. Likewise, LWT records during lactation were used to generate a daily LWT profile, similar to what has been done in previous studies such as Sneddon et al. (2017) and Chapter 2.

7.3.5.1 Live weight – pre-calving

A fourth-order Legendre polynomial was fitted to LWT data using random regression in ASReml (Gilmour et al. 2015) to obtain an average growth curve for each heifer from six to 21 months of age. The goodness of fit achieved with the overall model and for each treatment was evaluated using the relative prediction error (RPE) (O'Neill et al. 2013; Rook et al. 1990). The predictive ability of the fourth-order polynomial as indicated by the RPE was good (RPE=2.86%). Liveweights referred to hereafter are those generated by the LWT curve. The proportion of 21-month LWT achieved at 12 months of age (pctLWT21) was calculated by dividing each heifer's 12-month LWT by her 21-month LWT.

7.3.5.2 Live weight and BCS – post-calving

Following calving, heifers were weighed daily after milking. When a morning and afternoon LWT was recorded, the average of the two were used. For instances when only one LWT was recorded this value was used. Between 25th December 2017 and 10th January 2018, the LWT records were approximately 200 kg heavier for each heifer than the days prior to 25th December and after 10th January. These records were determined to be biologically implausible and deleted. There were 16,319 LWT records available for 94 heifers ranging from 97 – 211 records per heifer.

After cleaning, a fourth-order Legendre polynomial was fitted to the data using random regression in ASReml (Gilmour et al. 2015) to obtain an average LWT curve for each heifer from first calving to dry-off. Likewise, a fourth-order Legendre polynomial was fitted to the BCS data from 24 months of age (precalving) until dry-off. Body condition score at 15 months of age was left as actual BCS measured. Data for BCS was centred on the 1st June 2017 as the start of the season, whereas, LWT data was modelled against days in milk. The order of the polynomial selected was based on the lowest RPE. The predictive ability of the fourth-order polynomials for LWT and BCS during first lactation was the best (RPE of 4.53% and 4.32% for LWT and BCS, respectively).

Average LWT and BCS during lactation for each cow were obtained as the average of the predicted values of the polynomial function (Sneddon et al. 2017).

7.3.6 Statistical analysis

The residuals of all continuous traits analysed were normally distributed (P>0.05).

7.3.6.1 Liveweight, growth and conformation

Height at withers, girth and crown-rump length (6, 12 and 15 months of age; each age fitted separately) were analysed using general linear models in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The models included the fixed effects of treatment and LWT at the same age as a covariate. This was done to determine if the differences in conformation were due to LWT differences, or due to the proportional increase in stature relative to LWT.

Least squares means of BCS and LWTs (6, 9, 12 and 15 months of age) were estimated using a general linear model. The model included the fixed effect of treatment.

Least squares means of the LWT at 18 and 21 months of age were estimated using a general linear model that included the fixed effects of treatment, herd during mating and the interaction between the two. All conformation measurements at 21 months of age were analysed using the same model, with the addition of LWT at 21 months of age as a covariate.

Least squares means of LWT and BCS during lactation were estimated using a general linear model including the fixed effect of treatment, herd during mating, the interaction between the two and the covariate days from median date of calving.

7.3.6.2 Puberty

Age and LWT at puberty were analysed using general linear models with the fixed effect of treatment. The cumulative proportion of heifers pubertal by the PSM1 was analysed using survival analysis. Survival curves were obtained using Kaplan-Meier estimates.

Heifers that were not confirmed pubertal by PSM1 were censored to PSM1 + 1 day. Differences in proportion of heifers pubertal one, two and three cycles before mating were analysed using Chi-squared test from the Kaplan-Meier estimates.

7.3.6.3 Pregnancy

Differences between treatments in the proportion of heifers pregnant in the first cycle or pregnant by the end of the mating period were analysed using Chi-squared test.

Logistic regression was used to assess the effects of grazing herd during mating, age at puberty, or estimated number of cycles premating on the likelihood of conceiving in the first cycle (21 days) or becoming pregnant by the end of the mating period.

7.3.6.4 Calving

The cumulative proportion of heifers calved in respect to the PSC was tested using survival analysis. Survival curves were obtained using Kaplan-Meier estimates. Differences in proportion of heifers calved in the first 21 days (C21) of PSC were analysed using Chi-squared test. The mean calving date was analysed using a linear mixed model that included the fixed effect of treatment.

7.3.6.5 Reproductive performance during first lactation

The proportion of heifers treated for anoestrus was compared using Chi-squared test. The cumulative proportion of heifers mated in respect to the PSM2 (not including heifers treated for anoestrus) was tested using survival analysis. Survival curves were obtained using Kaplan-Meier estimates. The interval from PSM2 until first service was analysed using a general linear model that included the fixed effect of treatment; deviation from median date of calving was included as a covariate.

Differences in proportion of heifers mated in the first 21 days (SR21) from PSM2 were analysed using Chi-squared test; firstly, including all heifers present at mating (n=94) and secondly, without heifers treated for anoestrus (n=12 treated, n=82 not-treated). Differences in three-week and six-week in-calf rate were analysed using Chi-squared test; once including all heifers present at pregnancy diagnosis (n=93) and once excluding heifers treated for anoestrus (n=12 treated, n=81 not-treated). There were no differences between treatments whether anoestrus treated heifers were included or not; results are presented for all 94 heifers.

7.3.6.6 Milk production

Milk, fat, and protein yields, lactation length and SCS were analysed using a general linear model that included treatment as a fixed effect and days from median date of calving as a covariate. Herd during mating and its interaction with treatment was considered but removed from the models as it had no significant effect (P>0.05).

7.3.6.7 Power analysis

The hypothesis here is that the two treatments will differ in age at puberty but have similar first lactation milk production. Approximately 52 heifers per treatment were required (α = 0.05; β= 0.2) to detect a difference in age at puberty of 26 days (7%; standard deviation of 47 days). To allow for potential losses between six and 15 months of age, 55 heifers were allocated to each treatment. It was expected that approximately 52/55 heifers in each treatment would enter the dairy herd and lactate for at least one season (the others may not conceive at 15 months of age). This allowed 80% power of the experiment (α = 0.05; β= 0.2) to detect a difference of 43 kg milksolids (12%; standard deviation of 75 kg). The binary nature of the majority of the reproductive data means that the study has low power (for example, 32% power to detect differences of 10% in pregnancy rate). However, these are highly relevant traits, therefore, the binary reproductive data has been presented to provide an indication of reproductive performance to direct subsequent investigations.

7.4 Results

7.4.1 Live weight, growth and conformation

The LWTs for heifers in the two treatments are illustrated in Figure 7.2 and Table 7.1. Heifers in both treatments had similar LWT at six and 18 months of age (P>0.05; Table 7.1). Heifers in the Target treatment were heavier than the heifers in the Seasonal treatment from nine to just after 15 months of age (Figure 7.2). The target LWT at six and 15 months of age were 157.2 kg and 314.4 kg, respectively. Heifers in both treatments had similar LWT from just after 15 months of age up to 21 months of age, however, at 21 months of age, heifers were different in LWT (P<0.05; Table 7.1). Additionally, heifers in the Target treatment were a greater proportion (59.2%) of their 21-month LWT at 12 months of age compared with heifers in the seasonal treatment (56.3%; P<0.001).

Table 7.1 Target live weight (LWT) and least squares means of LWT ± SEM of heifers grown to Target (TAR) or in a Seasonal pattern (SEAS) from six to 15 months of age. Target LWTs were calculated by linear interpolation between targets at six, 15 and 22 months of age.

Age (months)	Target LWT (kg)	LWT (kg)	
		SEAS	TAR
6	157.2	160.4 ± 2.1	159.0 ± 2.1
9	211.4	193.7^{a} ± 2.2	204.6^{b} ± 2.2
12	269.1	245.7^{a} ± 2.5	264.0^{b} ± 2.5
15	314.4	310.4^{a} ± 2.9	322.9^{b} ± 2.8
18	378.7	393.7 ± 3.4	395.5 ± 3.3
21	444.4	435.2^{a} ± 4.0	448.0^{b} ± 3.8

Means within parameters, within rows with differing superscripts are significantly different (P<0.05).

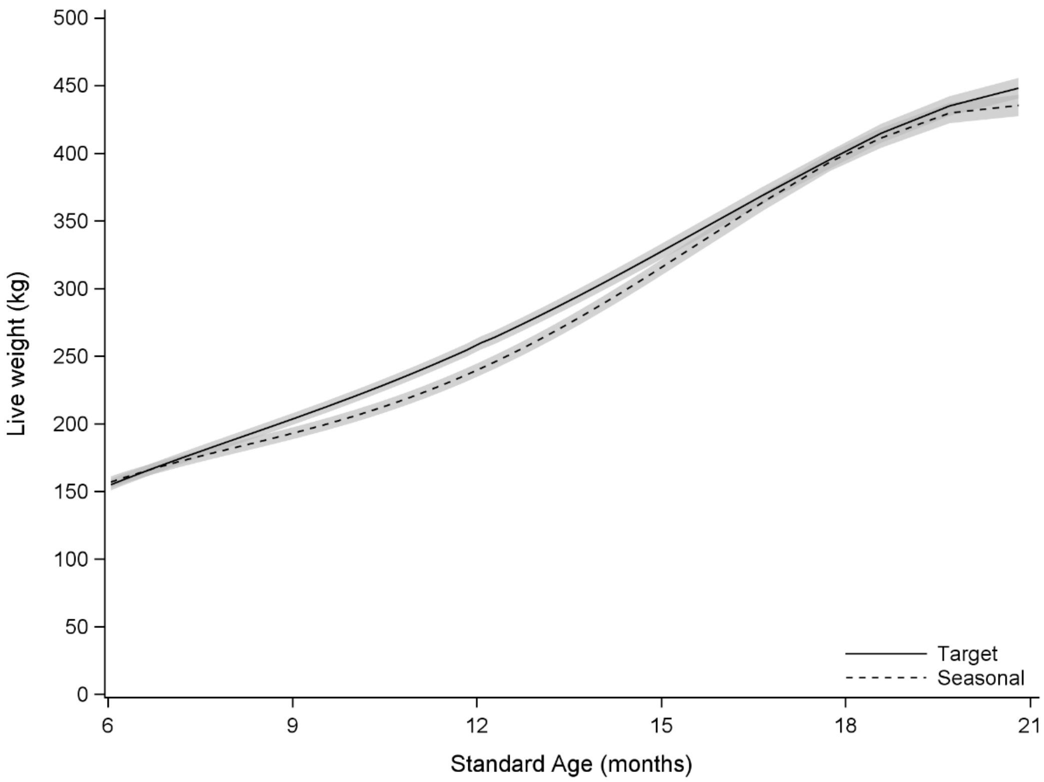

Figure 7.2 Predicted live weight of heifers grown to Target or in a Seasonal pattern from six to 15 months of age using a fourth order Legendre polynomial fitted to liveweight data from six to 21 months of age with random regression. Where standard age is calculated based on a birthdate of 26th July 2015 for all heifers. Grey shading indicates 95% confidence limits.

At six months of age, heifers in both treatments were similar in height, girth and length (P>0.05; Table 7.2). At 12 months of age, there were no differences between treatments in height and length, however, the heifers grown to target had greater girth circumference compared with heifers in the seasonal treatment (P<0.001; Table 7.2). By 15 months of age, girth and length were not different between treatments, however, there was a difference in height; heifers in the Seasonal treatment were 2 cm taller than those in the target treatment. Girth and length at 21 months of age were similar between treatments, however, heifers in the seasonal treatment were taller than those in the target treatment (Table 7.2). Body condition score at 15 months of age was not different between the two treatments (P>0.05; Table 7.2).

Table 7.2 Least squares means ± SEM of body condition score (BCS) and conformation measurements (height, girth, length) adjusted for live weight at each age of heifers grown to Target or in a Seasonal pattern from six to 15 months of age.

	Seasonal	Target	P-value
Height			
6 months (cm)	100 ± 0.3	100 ± 0.3	0.822
12 months (cm)	115 ± 0.3	116 ± 0.3	0.475
15 months (cm)	124^{b} ± 0.4	122^{a} ± 0.4	<0.001
21 months (cm)	127^{b} ± 0.4	126^{a} ± 0.4	0.032
Girth			
6 months (cm)	154 ± 0.7	153 ± 0.7	0.775
12 months (cm)	175^{a} ± 0.6	182^{b} ± 0.6	<0.001
15 months (cm)	195 ± 0.6	195 ± 0.6	0.833
21 months (cm)	219 ± 0.7	218 ± 0.7	0.440
Length (crown to rump)			
6 months (cm)	136 ± 0.8	136 ± 0.7	0.805
12 months (cm)	154 ± 0.5	155 ± 0.5	0.152
15 months (cm)	163 ± 0.6	164 ± 0.6	0.106
Length (wither to rump)			
15 months (cm)	117 ± 0.4	117 ± 0.4	0.816
21 months (cm)	128 ± 0.6	128 ± 0.6	0.772
BCS (1-10 scale)			
15 months	5.3 ± 0.1	5.3 ± 0.1	0.813

Values with differing superscripts within rows are significantly different (P<0.05).

7.4.2 Live weight and BCS during first lactation

Average LWT and BCS during first lactation were 441 kg and 4.4 BCS for heifers in the Seasonal treatment and 444 kg and 4.4 BCS for heifers in the Target treatment (P>0.05; Table 7.3). Heifers from both treatments were similar in LWT and BCS throughout first lactation (Table 7.3).

Table 7.3 Least square means ± SEM of live weight (LWT) and body condition score (BCS) during first lactation of heifers grown to Target or in a Seasonal pattern from six to 15 months of age. LWT were estimated from daily LWT records and BCS were measured on a 1-10 scale (Roche et al. 2007) from approximately monthly BCS records modelled using fourth-order Legendre polynomials.

	Seasonal	Target	P value
Live weight (kg)			
Average LWT	441.0 ± 4.2	444.0 ± 3.9	0.608
Post-Calving (DIM0)	436.2 ± 4.5	446.3 ± 4.2	0.107
PSM2	424.1 ± 4.1	425.2 ± 3.8	0.844
January	453.7 ± 4.4	454.6 ± 4.0	0.882
Dry-off	476.3 ± 6.8	464.5 ± 5.5	0.181
BCS (1-10 scale)			
Average BCS	4.4 ± 0.0	4.4 ± 0.0	0.550
Pre-Calving (10^{th} July)	5.6 ± 0.0	5.6 ± 0.0	0.478
PSM2	4.1 ± 0.0	4.2 ± 0.0	0.505
January	4.3 ± 0.1	4.3 ± 0.1	0.634
Dry-off	4.6 ± 0.1	4.6 ± 0.1	0.850

Where: DIM0=zero days in milk; day of calving measured after calving, PSM2=planned start of mating (18/10/2017), January=182 days in milk (approximately 17^{th} January 2018), dry-off=280 days in milk (approximately 1^{st} May).

7.4.3 Puberty

Eight heifers (6 Seasonal, 1 Target) did not meet the definition of puberty before PSM1 and were included in the analysis of the proportion of heifers that had reached puberty, but not in the age and liveweight at puberty analysis. Of these heifers, six (5 Seasonal, 1 Target) had one CL detected at one of the two concluding scans, whereas, two (Seasonal) were did not.

Figure 7.3 illustrates the cumulative proportion of heifers that reached puberty. There were differences between treatments early in the observation period (Wilcoxon $P<0.001$) and late in the observation period (Log-Rank $P<0.001$). Heifers that grew to target reached puberty 38 days younger ($P<0.001$), and 10 kg lighter ($P<0.05$) than heifers grown in a Seasonal pattern (Table 7.4). As a result, heifers grown to target were a lower percentage ($P<0.05$) of their estimated mature LWT at puberty compared with heifers grown in a seasonal pattern (48.4% vs 50.4%; Table 7.4). More heifers in the Target treatment were pubertal at one, two and three cycles before PSM1 (Table 7.4).

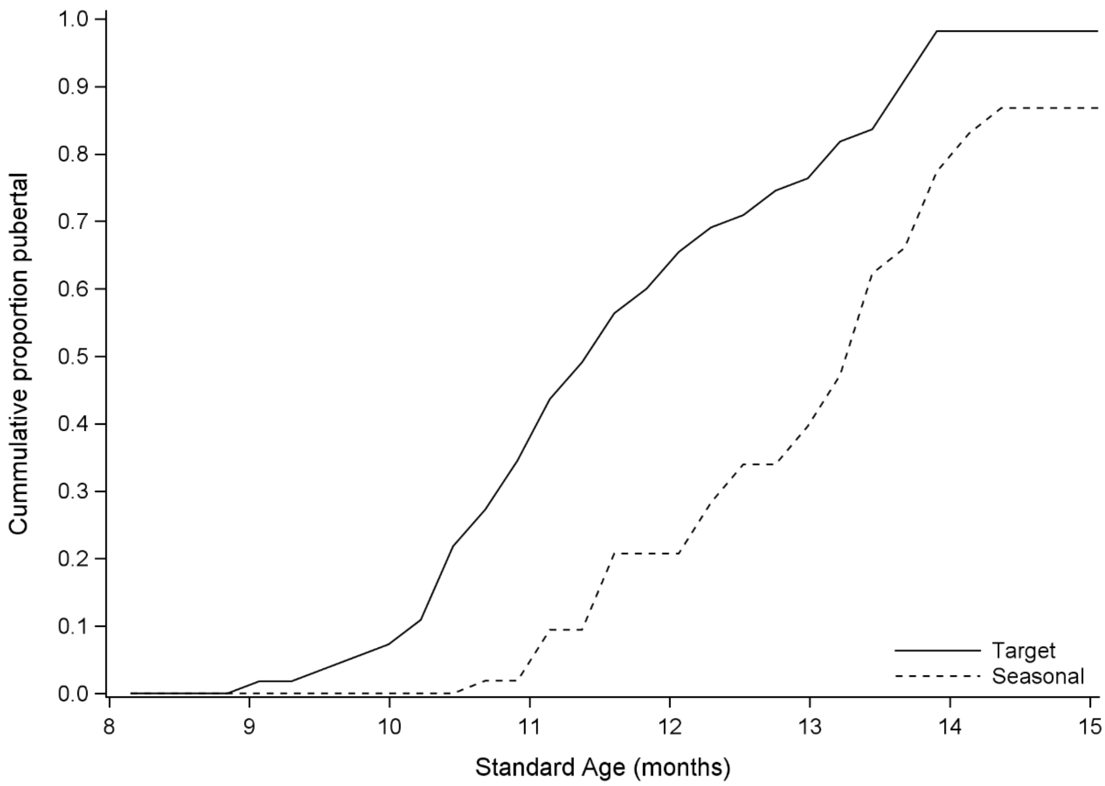

Figure 7.3 Cumulative proportion of heifers that had reached puberty before the start of mating at 15 months of age (PSM1) for heifers grown to Target or in a Seasonal pattern from six months of age to mating at 15 months of age. Where standard age is calculated based on a birthdate of 26th July 2015 for all heifers.

7.4.4 Pregnancy and first calving

A total of six heifers (5.5%; 6/108) were not pregnant by the end of the mating period. As mentioned earlier, two heifers were aborting at the time of pregnancy diagnosis. These heifers were considered to have been pregnant by the end of the mating period but were treated as missing values for pregnant at days 21 and 42. There were no differences (P>0.05) between treatments in the proportion that were pregnant in the first cycle, first two cycles (42 days) or by the end of the mating period (Table 7.4).

The median date of calving was the 1st August (five days after PSC) for both treatments. There were no differences in the cumulative proportion of heifers that had calved in respect to PSC (Wilcoxon and log-Rank P>0.05; Appendix VI). The proportion of heifers that calved by 21 days after PSC (C21) did not differ (P>0.05) between treatments (76% and 82% for Seasonal and Target, respectively).

7.4.4.1 Effect of puberty measures on pregnancy attainment

Heifers that were younger at puberty were no more likely to conceive in the first cycle than heifers that were older at puberty (OR 0.997; 95% CI 0.987-1.007; P>0.05), likewise, they were no more likely to conceive by the end of the mating period (OR 1.005; 95% CI 0.985-1.025; P>0.05).

7.4.5 Reproductive performance during first lactation

There were 90 heifers that had calved by the 30th August so were considered for anoestrus treatment. Twenty one percent (9/42) of heifers in the Seasonal treatment were treated for anoestrus, compared with 6% (3/48) of heifers in the Target treatment (P<0.05; Table 7.4). There were no differences in the cumulative proportion of heifers that were submitted for mating in respect to PSM2 (Wilcoxon and log-Rank P>0.05; Appendix VI). The proportion of heifers submitted for mating in the 21 days from PSM2 did not differ (P>0.05) between treatments (Table 7.4). The six-week in-calf rate for heifers in the "seasonal" treatment was 81.4%, similar (P>0.05) to the 88.0% found for the Target treatment group (Table 7.4). There were no differences between the two treatments in any of the reproductive outcomes.

Table 7.4 Least squares means ± SEM for age and live weight (LWT) at puberty, estimated percentage of mature LWT at puberty, and reproductive outcomes (%; n in parentheses) during first and second mating periods of heifers grown to Target or in a Seasonal pattern from six to 15 months of age. Where PSM1 is planned start of first mating as a 15-month old heifer and PSM2 is planned start of second mating during first lactation.

	Seasonal	Target	P value
First mating performance			
Age at puberty (days)	$380^{b} \pm 5$	$342^{a} \pm 5$	<0.001
LWT at puberty (kg)	$264^{b} \pm 4$	$254^{a} \pm 3$	0.039
Estimated % mature LWT at puberty	$50.4\%^{b} \pm 0.7$	$48.4\%^{a} \pm 0.6$	0.039
Proportion pubertal			
3 cycles before PSM1	$40\%^{a}$ (21/53)	$75\%^{b}$ (41/55)	<0.001
2 cycles before PSM1	$66\%^{a}$ (35/53)	$84\%^{b}$ (46/55)	0.035
1 cycle before PSM1	$87\%^{a}$ (46/53)	$98\%^{b}$ (54/55)	0.024
Proportion pregnant by			
21 days of PSM1	69% (36/52)	72% (39/54)	0.735
42 days of PSM1	88% (46/52)	93% (50/54)	0.467
End of mating period	92% (49/53)	96% (53/55)	0.375
Second mating performance			
Treated for anoestrus (%)	$21\%^{b}$ (9/42)	$6\%^{a}$ (3/48)	0.037
21-day submission rate	98% (43/44)	96% (48/50)	0.635
Interval from PSM2 to 1st service (days)	8.1 ± 1.0	9.0 ± 1.0	0.531
Proportion pregnant by			
21 days of PSM2	58% (25/43)	64% (32/50)	0.563
42 days of PSM2	81% (35/43)	88% (44/50)	0.375

Values with differing superscripts within rows are significantly different (P<0.05).

7.4.6 Milk production

Heifers that were grown in a seasonal pattern produced similarly (P>0.05) in first lactation to heifers that were grown to target (Table 7.5). Heifers lactated for approximately 280 days and produced over 330 kg of milksolids (Table 7.5). There were no differences in the composition of the milk (fat and protein percentages), nor the yields (Table 7.5). Somatic cell score was not different for heifers grown to target or in a seasonal manner (P>0.05; Table 7.5).

Table 7.5 Least squares means ± SEM of first lactation milk production of heifers grown to Target or in a Seasonal pattern from six to 15 months of age.

	Seasonal	Target	P-value
Days lactating (days)	281 ± 2	286 ± 2	0.106
Milk yield (L)	3,939 ± 83	4,029 ± 77	0.429
Energy-corrected milk yield (L)	4,330 ± 91	4,400 ± 84	0.575
Fat (kg)	178.6 ± 4.1	182.0 ± 3.8	0.549
Protein (kg)	151.7 ± 3.1	152.5 ± 2.9	0.842
Milksolids (kg)	330.3 ± 7.0	334.5 ± 6.5	0.662
Fat%	4.54 ± 0.06	4.53 ± 0.06	0.835
Protein%	3.86 ± 0.03	3.79 ± 0.03	0.121
Somatic cell score	4.93 ± 0.12	5.13 ± 0.12	0.237

7.5 Discussion

The design of the current study was to have the mean LWT of each treatment on target at six and 15 months of age. This aim was met, as the mean percentage of target LWT achieved at six months of age was 100% for both Seasonal and Target heifers, and was 98% and 103%, respectively, at 15 months of age. The New Zealand industry average six-week in-calf rate is 66% (Livestock Improvement Corporation & DairyNZ 2017). Heifers in the current study exceeded the industry average six-week in-calf rate for first pregnancy (88 and 93%, Seasonal and Target, respectively) and second pregnancy (81 and 88%, Seasonal and Target, respectively); as well as the industry target of 78% (Livestock Improvement Corporation & DairyNZ 2017). There are no industry targets for first lactation milk production, however, heifers in the current study produced more than the average for two-year-old Holstein Friesian heifers of 293.8 kg milksolids (330.3 and 334.5 kg, Seasonal and Target, respectively) and 3,571 litres milk (3,939 and 4,029 L, Seasonal and Target, respectively) (Livestock Improvement Corporation & DairyNZ 2017). These results suggest that the heifers in the current study were well managed and attained high performance for both reproduction and milk production.

7.5.1 Liveweight, growth and conformation

At six months of age, heifers in the current study were on target, with a mean LWT of 160 kg, 10 kg heavier than that of Friesian heifers reported by Meier et al. (2017) in a similar study. In the present study, heifers in the seasonal treatment grew in a similar pattern to those in the NZ dairy herd (Handcock et al. 2016), exhibiting slower growth from six to 12 months of age and faster growth from 12 to 15 months of age, whereas the heifers in the Target treatment grew close to linear trajectory. From 15 months of age, heifers in both treatments were similar in LWT. The average LWT during first lactation was approximately 440 kg, heavier than the average LWT (425 kg) of two-year-old NZ Holstein-Friesian heifers (Livestock Improvement Corporation & DairyNZ 2017). However, heifers in both treatments exhibited fluctuations in LWT throughout lactation and were 425 kg at PSM2, similar to the NZ average for Holstein-Friesian two-year-olds (Livestock Improvement Corporation & DairyNZ 2017).

The height of the heifers in the current study at six, 12, 15 and 21 months of age were similar to two studies reported in Friesian heifers in New Zealand (Macdonald et al. 2005; Meier et al. 2017). The length from shoulder to tail was also similar to those reported by Meier et al. (2017) at 15 months of age. Conformation measures were adjusted for LWT to determine if the differences in conformation were due to LWT differences, or due to the proportional increase in stature relative to LWT. Heifers of both treatments were similar in height and length at 12 months of age when adjusted for 12-month LWT. This indicates that the heifer's LWT growth was proportional to their stature growth. In contrast, when girth circumference was adjusted for LWT at 12 months of age, there was a difference between treatments. This may indicate that the heifers grown to Target may have had superior gastrointestinal tract and liver development compared with heifers grown in a seasonal pattern (Swali et al. 2008). By 15 months of age, the heifers that grew in a seasonal manner had caught up in and exceeded the height of heifers that grew to target but were similar in length and girth measurements. These results suggest that the heifers grown in a seasonal manner were proportionally taller, but not longer or rounder than the heifers grown to target. By 21 months of age, there was a 1 cm difference in height between the two treatments, in that the heifers in the seasonal treatment were taller. The lack of differences at 21 months of age for length and girth suggest that there was no permanent stunting of the frame size for heifers grown in a seasonal pattern, but when adjusted for LWT they were slightly taller. Together this indicates that the heifers grown in a seasonal manner may have been growing slightly more bone (height) at the expense of gaining LWT.

Body condition score at 15 months of age was 5.3 for both treatments, similar to the 5.4 that was reported by Meier et al. (2017) for Friesian heifers of similar age. Pre-calving, heifers from both treatments were at BCS 5.6; slightly above the recommended industry target for first-calving heifers of 5.5 (Burke et al. 2007). From calving to mating, heifers lost approximately one BCS unit, but by the end of lactation were gaining condition.

7.5.2 Reproductive performance

Heifers in the current study attained puberty between 48 and 51% of their estimated mature liveweight at puberty, similar to previous reports of 43 to 57% (Garcia-Muniz et al. 1998; Macdonald et al. 2005; McNaughton et al. 2002; Meier et al. 2017). Despite this, heifers that grew to target attained puberty approximately a month earlier and 10 kg lighter than heifers grown in a seasonal manner. This finding is in contrast to those of Le Cozler et al. (2009) who reported that puberty occurred at similar LWT but different ages in Holstein heifers grown at different trajectories between four and 12 months of age, and those of Lammers et al. (1999) who reported that Holstein heifers fed to achieve 1.0 kg LWT gain per day attained puberty at similar LWT but 32 days earlier than those fed to achieve 0.7 kg LWT gain per day. However, Little et al. (1981) reported that 23% of the variation in LWT at puberty was explained by LWT gain prior to puberty, with the fastest growing heifers reaching puberty at similar ages but greater LWTs than the slower growing heifers. In addition, Short and Bellows (1971) reported that as winter feeding level increased, the LWT at which beef heifers reached puberty also increased. Those authors attributed this to the increased feeding level accelerating body growth faster than physiological maturity, as measured by age at puberty. In the current study, heifers in the seasonal treatment were growing the fastest in the last few months leading up to PSM1. The increased feeding level and subsequent accelerated LWT gain of heifers in the seasonal treatment may have been faster than physiological maturity compared with that of the heifers in the target treatment.

The relatively small number of heifers included in the study and the binary nature of the majority of the reproductive data may limit the power of the statistical analyses to detect differences between treatments. Despite this, data on first pregnancy and rebreeding performance was recorded and hence has presented the opportunity to provide an indication of growth pattern effects on reproductive performance.

In the current study, more heifers (98%) in the Target treatment were confirmed pubertal before PSM compared with heifers grown in a seasonal pattern (87%). Both figures were greater than the 60% of heifers that were reported pubertal at the start of a heifer synchrony programme study (McDougall et al. 2013). In that study, more heifers with a BCS greater than 4.5 were pubertal than heifers with a BCS less than 4.5 (McDougall et al. 2013). The average BCS of heifers in the current study was 5.3 at 15 months of age, which may explain why more were pubertal in the current study compared with the study by McDougall et al. (2013). In addition, the definition of puberty was different for the current study compared with that of McDougall et al. (2013), heifers were blood sampled twice before the start of the synchrony programme and puberty was defined as at least one of two blood progesterone concentrations exceeding 1.0 ng/mL (McDougall et al. 2013).

Even though more heifers in the Target treatment were confirmed pubertal at PSM1 than the seasonal treatment, there were no differences in pregnancy rates or calving spread. Byerley et al. (1987) reported that fertility improved over the first few oestrous cycles and Johnsson and Obst (1984) reported that heifers that attained similar LWT at mating but had different proportions pubertal (81 vs 75%) resulted in differences in calving rate (85 vs 75%). However, in the current study, there was no effect of treatment, age at puberty or number of oestrous cycles on the probability of getting pregnant. Likewise, in Holstein-Friesian heifers from the USA, and in NZ dairy and dairy-beef crossbred heifers, there was no evidence to suggest that age at puberty was associated with the speed at which heifers conceived (Hawk et al. 1954; Hickson et al. 2011). Although some heifers did not meet the definition of puberty before PSM1, the majority of heifers in the current study had a CL present before PSM1. As first ovulation is often not accompanied by an observable oestrus (Berardinelli et al. 1979; Swanson et al. 1972), this may indicate that their first overt oestrus occurred when joined with the bull.

The results presented in Chapter 6 demonstrated that there were no differences in first calving 21-day calving rate between big Holstein-Friesian crossbred (FX) heifers (similar breed make-up and 21-month LWT to those in the current study) that were 56.3% or 59.2% pctLWT21 (84.3 ± 0.5% and 83.0 ± 0.5%, respectively). Heifers in the current study that were in the seasonal treatment had a 21-day calving rate of 76%, similar to that of heifers in the target treatment of 82%. Furthermore, stayability to first calving was similar for big FX heifers that were 56.3% and 59.2% pctLWT21 (95.1 ± 0.2% and 94.7 ± 0.2%, respectively). These studies indicate that a small difference in growth pattern (approx. 3% pctLWT21) was not sufficient to elicit a reproductive or survival response as measured by 21-day calving rate and stayability.

During the heifers' first lactation, there were few differences in reproductive performance. The proportion of heifers submitted for mating, and the three- and six-week in-calf rates did not differ between treatments. Similar to what has been reported in beef heifers grown to 55 or 62% of mature LWT at breeding, which resulted in a difference in age at puberty but no difference in proportion pregnant as heifers or at rebreeding (Lardner et al. 2014). The only difference identified in the heifers' reproductive performance during first lactation in the current study was in the proportion treated for anoestrus. More heifers grown in a seasonal pattern were treated for anoestrus than heifers grown to target. Nevertheless, these differences were between small numbers of heifers (3 target vs 9 seasonal), therefore, these results should be interpreted with caution. The results from Chapter 6 demonstrated that there were little to no effects of LWT or pctLWT21 on reproductive performance as second or third calvers; measured by 21-day calving and re-calving rates. Combined, these studies indicate that there are few carryover effects of LWT or growth prior to first calving on reproductive performance after first calving.

7.5.3 Milk production

First lactation milk production was similar for heifers grown to target or in a seasonal pattern from six to 15 months of age. Heifers produced approximately 4,000 L of milk and 330 kg of milksolids in first lactation, similar to Holstein-Friesian and Holstein-Friesian crossbred heifers that were approximately 500 kg at 21 months of age (Chapter 3). Heifers that were heavier at 12 months of age produced greater quantities of milk in their first lactation and accumulated over three lactations compared with heifers that were lighter (Chapter 3). In the current study, there were no carry-over consequences in terms of milk production despite heifers in the seasonal treatment being approximately 20 kg lighter at 12 months of age than heifers in the Target treatment. A reason for this may be that the LWT difference between the treatments was only maintained from approximately nine to 15 months of age, after which the heifers were similar in LWT. This six-month period of LWT difference may not have been long enough to invoke a milk production difference. Furthermore, there were no differences in first lactation ECM between big FX heifers that were 56.3% or 59.2% pctLWT21 (4,131.1 ± 20.4 and 4,189.9 ± 20.4 kg, respectively; Chapter 4). Likewise, there were no differences between average FX heifers that were 56.3 or 59.2% pctLWT21 (4,024.7 ± 20.4 and 4,076.1 ± 20.4 kg, respectively; Chapter 4). Combined, these studies indicate that a small difference in growth pattern (approx. 3% pctLWT21) was not sufficient to elicit a milk production response.

There was a 20 kg difference in 12-month LWT between the two treatments, it may have been more appropriate to generate a larger difference in LWT. For example, a difference of 30 kg (6% pctLWT21) for these two treatments (269/444=60% for Target and 239/444=54% for Seasonal) may result in a milk production difference based on the results from Chapter 4. Holstein-Friesian crossbred heifers that were 54% pctLWT21 and average in 21-month LWT had first lactation ECM yields of 3,981.2 ± 20.5 kg ECM, less than 4,089.6 ± 20.5 kg ECM for heifers that were 60%. Similar results were found for FX heifers that were big at 21 months of age, however, further research would need to be completed to investigate this hypothesis further.

7.6 Conclusions

Heifers that grew according to industry target LWT trajectory attained puberty earlier than heifers that grew according to industry norms of slow during winter and fast during spring. Nevertheless, there was no difference in date of first calving between the two treatments. Additionally, heifers that grew in a seasonal pattern produced similar quantities of milk in first lactation to heifers that grew according to industry targets. Results from this study provided an indication of growth pattern effects on reproductive performance. There were no differences between the two treatments in six-week pregnancy rates for first or second pregnancy. These results suggest there were limited disadvantages to growing heifers slower over their first winter, provided they caught up to target LWT by first mating.

Chapter 8 General Discussion

8.1 Introduction

A successful dairy cow in a seasonal pasture-based system could be defined as one who among other things: conceives within three weeks of the planned start of the mating (PSM), produces above average milk production, continues to conceive within six weeks of PSM each year and ultimately survives in the herd long enough to generate profit for the farmer/herd owner. Factors affecting any of these qualities will impact farm profitability.

Previous research has demonstrated that LWT and growth rate of dairy heifers had impacts on age at puberty (Lammers et al. 1999; Macdonald et al. 2005), earliness of first calving, but not subsequent calvings (Archbold et al. 2012; McNaughton & Lopdell 2013), probability of calving each year (Archbold et al. 2012; Vargas et al. 1998) and milk production (Dobos et al. 2001; McNaughton & Lopdell 2013; van der Waaij et al. 1997; Van Eetvelde et al. 2017). There are few studies on the effects of growth rate on reproductive performance, most of these studies focus on preweaning growth (Davis Rincker et al. 2011; Raeth-Knight et al. 2009) and not growth between three months of age and first calving when heifers are no longer reliant on milk as a feed source. There is evidence that rapid growth rates during the pre-pubertal allometric phase of mammary development can cause reduced milk production (Macdonald et al. 2005; Sejrsen 1994). Therefore, it could be expected that there would be a limit as to how fast a heifer can be grown before her milk production is negatively impacted.

Furthermore, the majority of studies on reproductive performance and milk production as related to LWT or growth are completed on heifers of Holstein or Holstein-Friesian breed makeup and in total-mixed-ration (TMR) environments (Archbold et al. 2012; Davis Rincker et al. 2011; Dobos et al. 2001; Ducker et al. 1982; Lammers et al. 1999; Raeth-Knight et al. 2009; Van Eetvelde et al. 2017), with few studies including Jersey and/or crossbreeds (Macdonald et al. 2005; McNaughton & Lopdell 2013; van der Waaij et al. 1997; Vargas et al. 1998).

The Holstein-Friesian-Jersey (FxJ) crossbreed is the dominant breed category in New Zealand (47.8%) (Livestock Improvement Corporation & DairyNZ 2018). Due to this large proportion of crossbred animals in the national herd, it is important to test if the effects of LWT or growth on milk production differ based on breed. In addition, due to the seasonal variations in pasture quality and quantity that occurs in the New Zealand pasture-based farming system (Litherland et al. 2002), dairy heifer LWT and growth pattern exhibits marked fluctuations from birth until first calving (Handcock et al. 2016; McNaughton & Lopdell 2012). The general aim of this thesis was to investigate the effects of LWT and growth on dairy heifer performance in the New Zealand pasture-based system.

8.2 Ideal LWT ranges for milk production and reproductive performance

Based on the findings reported in this thesis, for heifers that were below average in LWT, significant improvements to milk production (Chapter 3), stayability (Chapter 5) and reproductive performance (Chapter 6) would be expected by increasing LWT. For heifers that were above average in LWT, significant improvements to milk production would be expected by increasing LWT, however, at the heaviest LWTs a reduction in stayability and reproductive performance was observed. This effect is illustrated in **Error! Reference source not found.** for LWT at 15 months of age for FJ heifers.

The greatest benefits to reproduction, stayability and milk production would be expected by increasing LWT of heifers in the LWT range indicated by the red band (170 – 273 kg; **Error! Reference source not found.**). As discussed in Chapters 5 and 6 there were LWT ranges where stayability and 21-day calving rates were deemed “good” or above industry targets. Combining the ranges from Chapters 5 and 6 for FJ heifers gives a range between 273 and 402 kg at 15 months of age for good reproductive performance, however, the difference in milk production between heifers at the lower end of that range and the upper end was substantial. For example, the expected difference in ECM yield of a 290 kg versus 360 kg FJ heifer was 536 kg in first lactation (3,880 kg vs 4,416 kg) and 1,484 kg accumulated over three parities (10,480 vs 11,964 kg), whereas, stayability to first, second and third calvings were similar (93.2 vs 94.0% for first, 77.2 vs 79.6% for second and 63.8 vs 65.0% for third) and first calving 21-day calving rates were also similar (81.5 vs 81.0%). Therefore, to balance the need for good reproductive performance and milk production as related to 15-month LWT a smaller band of LWT was identified as the ideal 15-month LWT range for FJ heifers, this range was from 350 to 402 kg (green band in **Error! Reference source not found.**). For 15-month LWT greater than 402 kg, there would be an increase in milk production, however, this would come at a cost to reproductive performance (**Error! Reference source not found.**).

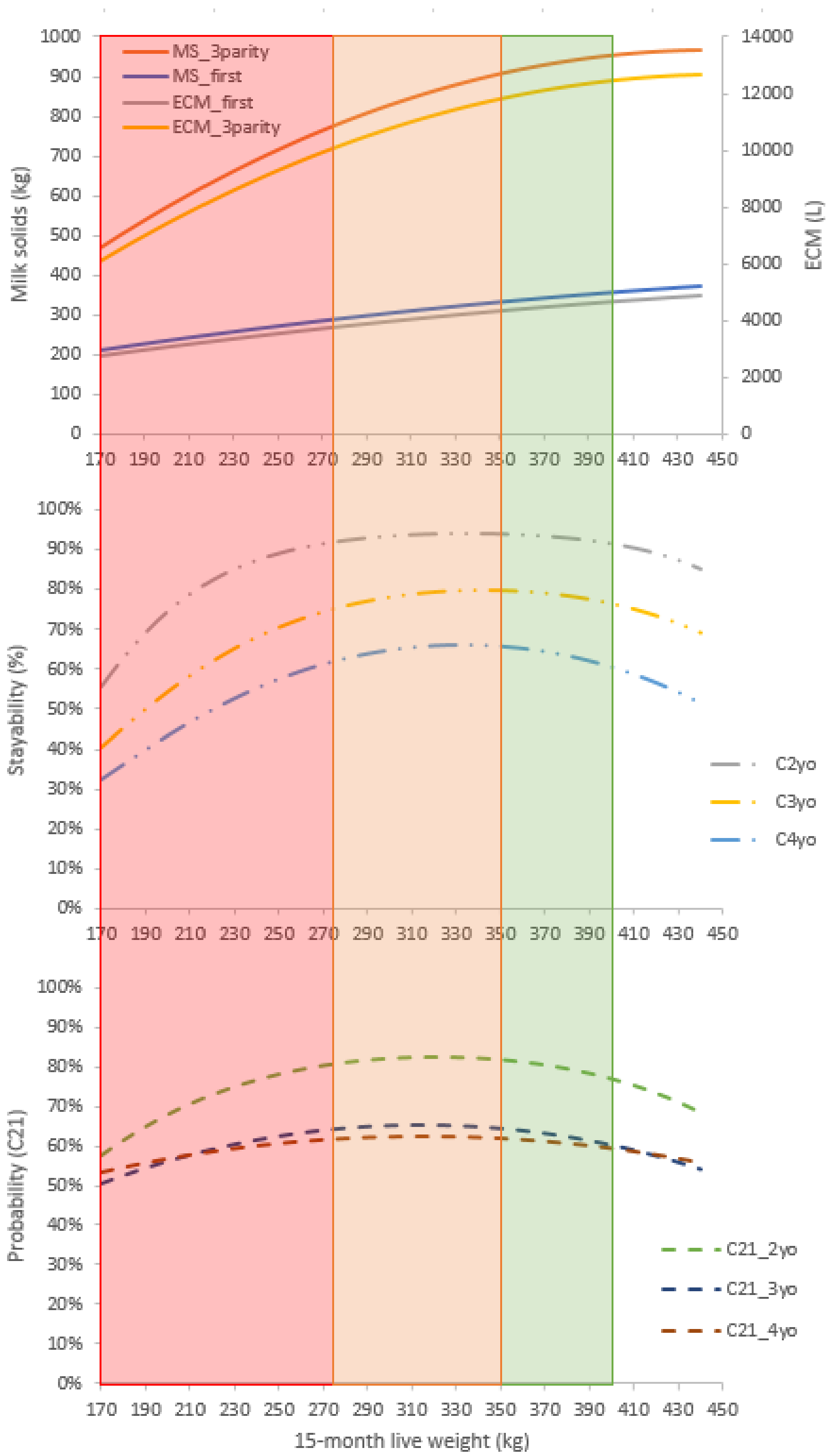

Figure 8.1 Relationships between 15-month live weight (LWT) and milk production (milksolids; MS and energy-corrected milk; ECM) and reproduction (stayability and 21-day calving rates; C21) for Holstein-Friesian-Jersey crossbreds. The LWT range where both reproduction and milk production were poor (red band), reproduction was good, but milk production was poor (orange band), "ideal range" of good reproduction and milk production (green band) and where reproduction declined but milk production was good (white band).

Based on previous studies, it was expected that there would be a positive relationship between heifer LWT and milk production, however, these previous studies (Dobos et al. 2001; McNaughton & Lopdell 2013; van der Waaij et al. 1997; Van Eetvelde et al. 2017) only reported linear effects and did not test for a quadratic effect. Results from Chapter 3 has built on the previous studies and showed that the relationship was predominantly curvilinear, meaning that the milk yield response to increasing LWT was greater in lighter heifers than in heavier heifers. Similarly, the greatest response to increasing LWT occurred for the lightest heifers for stayability and first calving 21-day calving rate (Chapters 5 and 6). This finding was not unexpected as Archbold et al. (2012) demonstrated that the largest difference between LWT categories at first mating for Holstein-Friesians was between the lightest (<290 kg) and second lightest (291 – 316 kg) heifers for both calving date (10 days) and longevity (6%). What was unexpected was the decline in stayability and probability of calving early at heavier LWTs. This effect was consistent across ages (six, 12 and 15 months of age) and breed groups. Archbold et al. (2012) reported that the reproductive performance of the heaviest Holstein-Friesians in their study (>343 kg) was similar to that of the second lightest heifers (317 – 342 kg).

Body condition score records were not available for heifers in the current study, however, it is likely that heifers at the very heavy end of the LWT range were in greater condition compared with the lighter heifers, due to the positive phenotypic and genetic (Pryce & Harris 2006; Veerkamp & Brotherstone 1997) correlations between LWT and BCS in dairy cattle. The rate of body tissue reserve loss (observed as BCS loss) is greatest in early lactation (Chapter 7) to support the energetic demands of lactation (Pryce & Harris 2006). Therefore, heifers that were heavier would likely have had more body tissue able to be mobilised and hence had partitioned more energy into milk production and were not able to put as much energy into reproduction (Butler & Smith 1989; Garnsworthy & Topps 2010). Further research on these complex relationships between heifer LWT, milk production and reproductive performance needs to be completed that includes both LWT and BCS records in order to confirm the hypothesis that heavier heifers have higher BCS than lighter heifers and that this is contributing to the superior milk yields but lower reproductive performance of heavier heifers.

Out of these four LWT ranges identified in **Error! Reference source not found.**, there were 5.5% of FJ heifers included in the study that were within the “ideal” LWT range of 350 to 402 kg. The range with the greatest proportion (75%) of heifers was the 273 to

350 kg range of "good reproductive performance but only average milk production". Therefore, for the majority of heifers, increasing LWT at 15 months of age to between 350 and 402 kg would be of great benefit to milk production, without compromising on reproduction. In contrast, only 0.1% (n=45) of the FJ heifers included in the study were heavier than 402 kg, that were deemed "too heavy". Therefore, for the majority of farmers, having 15-month-old heifers that were "too heavy" is highly unlikely to be an issue. What is more likely to be an issue is heifers that were too light; 19.3% of the FJ heifers included in the study were less than 273 kg. Heifers that were in this "band" were at risk of having poor milk production and reproductive performance, therefore, management strategies to increase the LWT of these lightest heifers would have the greatest benefits to both milk production and reproduction. Interestingly, 39% of herds with FJ heifers had all of their heifers heavier than 273 kg at 15 months of age, whilst, 35% had up to a quarter of their heifers lighter than 273 kg at 15 months of age, indicating these herds should focus on improving the growth of the tail-end. The remaining 26% of herds had more than 25% of their heifers below 273 kg, and therefore, should focus their efforts on improving heifer growth overall.

These four LWT ranges that have been identified for 15-month-old FJ heifers in **Error! Reference source not found.** have also been identified for the other breed groups studied (F, FX, JX and J; Appendix VII) and at other ages (six and 12 months of age) and are displayed in **Error! Reference source not found.**. For J heifers, there was no identified "orange zone" for any of the ages studied due to the narrow range identified for good reproductive performance of J heifers (Table 8.1). As mentioned earlier, LWT after 15 months of age was not used as a predictor of reproductive performance in this thesis due to the animals already being pregnant (or not) at these ages. Therefore, an ideal LWT range for 18 or 21 months could not be suggested as has been done for six, 12 and 15 months of age. However, the stayability to second and third calvings were greatest for heifers categorised as big or huge at 21 months of age for all breed groups other than J (Appendix IV). Similarly, milk production was also the greatest for big and huge heifers within breed group (Chapter 4), thereby suggesting that heifers that were categorised as big and huge at 21 months of age would have the best milk production and stayability. There were only small differences between LWT categories in 21-day calving and re-calving rates for second and third calvings (Appendix V), indicating that there was little to no effect of 21-month LWT on the earliness of calving in second or third lactations. For FJ heifers, those that were between 426 and 445 kg at 21 months of age were categorised as big (Table 4.2), and those greater than 445 kg were huge. These LWT ranges provide a good starting point for the ideal range in 21-month LWT for FJ heifers.

Table 8.1 Ranges in live weight (LWT; kg) at six, 12 or 15 months (mo) of age where reproductive performance and milk production were poor, average, good or best.

Breed	Age (mo)	Poor repro, poor milk (red)	Good repro, average milk (orange)	Good repro, good milk (green)	Repro declines, best milk (white)
F	6	<161	161 - 200	200 - 234	>234
	12	<245	245 - 285	285 - 318	>318
	15	<314	314 - 360	360 - 390	>390
FX	6	<136	136 - 190	190 - 243	NA
	12	<217	217 - 285	285 - 337	>337
	15	<280	280 - 355	355 - 398	>398
FJ	6	<133	133 - 190	190 - 229	>229
	12	<212	212 - 280	280 - 316	>316
	15	<273	273 - 350	350 - 402	>402
JX	6	<130	130 - 175	175 - 205	>205
	12	<209	209 - 265	265 - 290	>290
	15	<267	267 - 330	330 - 357	>357
J	6	<152	-	152 - 169	>169
	12	<227	-	227 - 261	>261
	15	<286	-	286 - 314	>314

F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

8.3 Target liveweights and breeding values

The current recommended target LWTs are 30% of mature LWT at six months of age, 60% at 15 months of age and 90% pre-calving for all breeds of dairy heifers (DairyNZ 2015a; Troccon 1993). Linear interpolation between the targets correspond to 50% at 12, and 86% at 21 months of age (DairyNZ 2015a). The weighted average LWT of Holstein-Friesian-Jersey crossbred cows (n=6,302) aged between five and eight years of age was 480.8 kg (Livestock Improvement Corporation & DairyNZ 2018). The current industry targets would be 144, 240, 288 and 413 kg at six, 12, 15 and 21 months of age, respectively; all of which were within the LWT range identified as “good reproductive performance and average milk production” (orange) in this thesis (Table 8.1). Liveweight BVs have been used to predict mature LWT of dairy heifers (Bryant et al. 2004; Handcock et al. 2016; McNaughton & Lopdell 2012). At an individual animal level, LWT BVs have a low accuracy due to Mendelian sampling and misidentification of dams and/or sires (Bowley et al. 2012); therefore, it is better to use a group average LWT BV instead of individual BVs. Currently, it is recommended to add a base value of 500 kg to the mean LWT BV of a group of heifers to predict their mature LWT (DairyNZ 2018g). Based on the May 2017 LWT BVs, the FJ heifers included in this thesis had a group average estimated mature LWT of 490.8 kg (mean LWT BV of -9.2 kg). The corresponding target LWTs would be 147, 245, 294 and 422 kg at six, 12, 15 and 21 months of age, respectively; again, all of which were within the “orange” LWT range identified as “good reproductive performance and average milk production”.

The corresponding estimated mature LWTs based on LWT BVs for F, FX, JX and J heifers were 532.0, 508.7, 474.1 and 447.7 kg, respectively. The target LWTs for FX and JX heifers at six, 12 and 15 months of age based on these estimates of mature LWT were within the LWT range identified as “good reproductive performance and average milk production”; likewise, for F heifers at 12 and 15 months of age. However, for J heifers, the corresponding target LWTs were within the LWT range identified as “poor reproductive performance and poor milk production” at six, 12 and 15 months of age and for F heifers at six months of age.

Based on the estimates of mature LWT from LWT records or LWT BVs, the LWT ranges suggested in this thesis for good reproductive performance and milk production of New Zealand dairy heifers are likely to be heavier than the current industry target LWTs. This indicates that either the estimates of mature LWT are too low or that the current target LWTs are too low, or potentially both. In a New Zealand study, the majority of high country breeding ewes never reached their potential size due to a restricted nutritional environment and the annual burden of producing and suckling a lamb (Coop 1973). Accurate estimates of mature LWT can only be obtained when animals are fed to ad libitum or to their genetic potential (Coop 1973; Fitzhugh & Taylor 1971), therefore, it is unlikely that pasture-based dairy cattle in New Zealand will have sufficient nutrient intakes to reach their genetic potential for LWT (Kolver & Muller 1998). Additionally, there have been no published studies comparing the relationships between LWT BV as a heifer (either as an individual or a group average) and actual mature LWT recorded (likely due to the low numbers of animals with both heifer and mature LWTs). Further research on “true” mature LWT, relationships between LWT at young ages and mature LWT, and prospective research studies on how to grow heifers to meet the LWTs identified in this thesis need to be completed. Despite this, a clear message arising is that having heifers too light is a far greater issue than having them too heavy.

For the reasons outlined above, LWT BVs were not used to estimate mature LWT for the analysis of the industry dataset (Chapters 2, 3, 4, 5 and 6). The aim of Chapter 7 was to grow heifers to “industry targets”, the heifers used in the experiment were from the two Massey University dairy farms that have good recording of ancestry and confirmed parentage with DNA testing. Additionally, both these farms regularly record cow LWTs and these are used in the estimates of LWT BV, therefore, it was deemed appropriate to use the group average LWT BV to estimate mature LWT and hence target LWTs for these well-recorded heifers. It would be of interest to analyse the relationship between LWT BV used for Chapter 7 and the heifers actual mature LWT attained in the future.

Currently in the New Zealand beef cattle industry, LWT BVs for birth, 200 day, 400 day, 600 day and mature LWT are estimated (Graser et al. 2005). There were positive genetic correlations (0.66 – 0.85) between LWT at young ages and LWTs after first calving in beef cattle (Costa et al. 2011; Williams et al. 2009). Therefore, an alternative to using only LWT records after first calving to estimate mature LWT BV in dairy cattle would be to include LWT records prior to first calving in the models for mature LWT in dairy cattle. Currently, due to the large proportion of two-year-old LWT compared with mature cow LWT records in the national database; a model to scale up LWTs from cows aged five years and younger to mature equivalents has been implemented (DairyNZ 2015b). The mature equivalent LWTs are then run through the animal evaluation model to calculate LWT BVs (DairyNZ 2015b). A similar methodology could be utilised for LWT records prior to first calving which may increase the accuracy of the current mature LWT BV.

An alternative to using mature LWT BVs to estimate a dairy heifer's mature LWT and hence target LWTs would be to generate LWT BVs at set ages from birth until first calving, similar to the 200, 400 and 600 day BVs used in the beef industry (Graser et al. 2005). Similar to how the mature LWT BV is an estimate of the animal's genetic potential for LWT, these younger LWT BVs would be estimates of the dairy heifer's genetic potential for growth throughout rearing, rather than her final mature LWT. These "growth" BVs could be used for target LWTs instead of relying on mature LWT BVs. As reported in Chapter 2, crossbred heifers are heavier than the average of their parental breeds, due to the positive effects of heterosis on LWT. Production values (PVs) are an estimate of an animal's future production. It is defined as the BV with the addition of non-additive genetic effect, permanent environmental effect and average heterosis effects (Harris et al. 1996). Consequently, PVs measure the "lifetime producing ability of the cow" and not the genetics she passes on to her progeny; which is what BVs measure. McNaughton and Lopdell (2013) recommended that when setting target LWTs for crossbred heifers the use of LWT PVs, instead of LWT BVs would provide a more accurate estimate of mature LWT, as it accounts for heterosis for LWT. Hence, further research into the estimation and use of LWT BVs and/or PVs between birth and first calving for target LWTs for dairy heifers is warranted.

8.4 Liveweight as a proportion of 21-month liveweight

Absolute growth rate (AGR or average daily gain; ADG) is the simplest model to describe the relationship between LWT and age (Fitzhugh 1976). The use of AGR is only useful for short periods of growth and does not provide much insight into the pattern of growth over time (Fitzhugh 1976). Furthermore, AGR over a set period is related to LWT and growth rate prior to and after the growth period studied (Bourdon & Brinks 1982; Roche et al. 2015). Retrospective studies that analyse the relationship between growth rate and performance variables (e.g. milk production) are difficult to complete and interpret as it is difficult to ascertain that it is the growth rate causing the effect and not the LWT prior or LWT after (Roche et al. 2015). Therefore, growth in proportion to a final end point is justified as a better representation of growth rate or growth pattern effects on milk production (or reproduction). Ideally, mature LWT would be used as the end-point, however, as mentioned previously, mature LWTs were not available for heifers in this thesis. Instead, LWT at 21 months was used as the end-point as this information was available for all heifers, regardless of whether they calved or not, allowing the inclusion of heifers that failed to calve.

One of the aims of this thesis was to explore the relationships between growth pattern during rearing and subsequent milk production and reproductive performance. One of the periods of slowest growth of heifers has been demonstrated to occur between five and 12 months of age (Chapter 2 (McNaughton & Lopdell 2012)). Which corresponded to only 12% of heifers being above target LWT when they were 12 months of age compared with 25% at 15 months of age (Handcock et al. 2016). For this reason, LWT at 12 months of age as a proportion of LWT at 21 months of age (pctLWT21) was used as an estimate for growth pattern up to 21 months of age (Chapters 4, 5, 6 and 7).

It is difficult to ascertain that it is the growth rate causing the effect and not the LWT prior or LWT after the growth period studied. It was therefore deemed appropriate to estimate the effect of pctLWT21 at a set 21-month LWT on milk production, reproduction and stayability, as this sets pctLWT21 to a common denominator. It is not possible to model a continuous variable (e.g. pctLWT21) nested within another continuous variable (e.g. 21-month LWT), therefore, 21-month LWT was grouped into five categories within each breed group and the linear and quadratic effects of pctLWT21 were nested within each combination of breed group and LWT category (Chapter 4). Within each breed group-LWT category, heifers that were heavier at 12 months of age were a greater pctLWT21 compared with heifers that were lighter at 12 months of age, as they both were similar in LWT at 21 months of age. Furthermore, heifers that were a lesser pctLWT21 exhibited greater fluctuations in growth rate from three to 21 months of age compared with heifers that were a greater pctLWT21 (Chapter 4). Heifers that were a greater pctLWT21 produced more milk during first and three-parity lactation than heifers that were a lesser pctLWT21 (Chapter 4). This illustrated that increased growth in the first 12 months of a heifer's life (compared with the second 12 months) was beneficial to future milk production; however, the relationships between pctLWT21 and stayability, calving and re-calving rates were inconsistent (Chapters 5 and 6).

There are few studies on the effects of LWT and growth on reproduction in dairy cattle (Bach 2011; Davis Rincker et al. 2011; Macdonald et al. 2005), most of these studies focus on preweaning growth in both beef and dairy cattle, or the effects of growth (preand postweaning) on puberty or milk production, and not subsequent reproductive performance. Additionally, the heifers in the study by Macdonald et al. (2005) were synchronised for oestrus before first mating, therefore, it was not possible to distinguish what impact the delayed onset of oestrus for the slower growing heifers may have had on final reproductive performance. A recent study based in Ireland reported that growth rate from birth to first mating had a linear relationship with heifer fertility, as measured by the interval (in days) from PSM to conception (Hayes et al. 2019). Heifers that grew faster between birth and PSM had a shorter interval between PSM and conception compared with heifers that grew slower (Hayes et al. 2019). Similar to the current study, the heifers included in the study by Hayes et al. (2019) were a mixture of Jersey and Holstein-Friesian, however, it was not reported if the breeds differed in their relationship between growth rate and reproduction. Furthermore, it is difficult to ascertain that it is the faster growth rate causing the effect and not the heavier LWT at PSM.

Based on the results from Chapters 4, 5, 6 and 7 there were no clear “targets” for recommended growth up to 12 and 21 months of age for dairy heifers and further research is therefore warranted to be able to provide clear recommendations to the industry.

8.5 Limitations of the thesis and recommendations for future research

The general aim of this thesis was to investigate the effects of LWT and growth on dairy heifer performance in the New Zealand pasture-based system. There is ample evidence presented in this thesis for the significant impacts of LWT and growth on subsequent performance; however, new questions have developed from these results that justify further research.

The heifers used for the industry dataset of this thesis were a sample of heifers that had LWT records with Livestock Improvement Corporation, therefore, they were a convenience sample and not a randomly selected sample of New Zealand dairy heifers. The milk production and stayability of the heifers in this dataset were comparable to that of industry (Livestock Improvement Corporation & DairyNZ 2017), and are therefore likely to be a good representation of heifers reared in New Zealand. However, there is a potential bias as the heifers that were weighed (and hence included in the study) may have been from herds that were actively monitoring heifer growth and performance, whereas, heifers that were not included in the study were likely from herds where they were not weighed and actively monitored. Consequently, the proportion of heifers in New Zealand that are light/poorly grown may be greater than that reported here. Additionally, to maintain a 20% replacement rate with close to five million dairy cattle in New Zealand (Livestock Improvement Corporation & DairyNZ 2017), there would be approximately one million dairy heifers reared in New Zealand per year. The largest year group included in this thesis was the 2013-born heifers, with 81,935 heifers that met the criteria for breed proportions and LWT records (Chapter 2). Based on that estimate of the number of dairy heifers reared per year, only 8% have regular LWT records prior to first calving. Although this is a numerically large study population, it represents only a small population of New Zealand dairy heifers.

Furthermore, the reliance on farmer recorded data for Chapters 2, 3, 4, 5 and 6 in this thesis has limited the "richness" of data available to analyse. Data records were selected based on heifers having a suitable number of LWT records before first calving (Chapter 2). The number of heifers with a good number of herd test records (three to four per lactation) was small (approximately 40% of first-calving heifers had three or more herd tests). Therefore, the datasets used for Chapters 3 and 4 likely had a small proportion of heifers with a recorded low milk yield that was a result of low number of herd tests to predict the yield, and not true low milk production. Due to LWT and growth being the key factors investigated in this thesis, the milk production data had to be restricted in this way, which has limited the analysis as it was unclear which heifers had true low production and which heifers had low number of herd tests.

The recording of final herd removal dates and reasons was poor, and hence stayability was used as a measure of survival instead of "true" survival. Stayability is a good measure of survival of dairy cattle (Hudson & Van Vleck 1981), however, the information on why or when an animal was removed is missing. The results from Chapter 5 indicated that LWT and growth had significant impacts on stayability, however, it was not known at which stage it had an impact. Kerslake et al. (2018) reported that the most common cause of removal (cull, sold or death) from the New Zealand dairy herd was for reproductive reasons (abortion, non-pregnant or low fertility; 34.9% of removals) followed closely by "unknown" reasons (29.2%). The proportion removed due to low milk production was only 8.6% of removals (Kerslake et al. 2018), therefore, it is likely that the majority of the animals included in this thesis that failed to calve, did so due to reproductive reasons and not low milk production.

Moreover, the dataset used for stayability was based on an animal having a recorded calving date or not, there was no requirement for any milk production records due to the reasons outlined previously. Future research should be directed at understanding how LWT at young ages impacted stayability and at what stages LWT elicited its effects.

The "key" measure of reproductive performance in New Zealand dairy herds is the six-week in-calf rate, however, due to a small proportion of heifers included in the study having sufficient early-aged pregnancy diagnosis data, calving rate and re-calving rates were analysed instead of pregnancy rates. Previous studies have suggested that re-calving rates can be used as a proxy measure for in-calf rates when no pregnancy diagnosis information is available (Brownlie 2012; DairyNZ 2018e). However, it should only be interpreted as an estimate (DairyNZ 2018e), due to the animals not calving for reasons other than failure to conceive or maintain a pregnancy. Results from this thesis demonstrated that LWT had an impact on calving and re-calving rates, however, it was not known if LWT impacted the proportion of heifers that conceived in the mating period, or on the proportion that failed to remain pregnant, or both. Furthermore, it was difficult to identify heifers that calved to a previously synchronised mating, as a result, heifers that were synchronised or treated for anoestrus but not recorded as such could not be removed from the dataset. In a study from a New Zealand research project that required mandatory recording, 8.9% of records for calving data had a corresponding anoestrus treatment recorded (Brownlie et al. 2014). It could be assumed that the proportions of animals treated for anoestrus in the current study is similar to that reported by Brownlie et al. (2014), however, it is not known which heifers' were treated and if lighter or heavier heifers were more or less likely to be treated. This is a limiting factor for our study, and is a known issue for genetic selection for fertility in New Zealand (Bowley et al. 2015).

As discussed previously, BCS records were not available for the industry dataset used for Chapters 2 – 6 in this thesis. Additionally, measurements of stature (wither height, length etc.) were also not available. Therefore, two heifers that were similar in LWT may have differed in stature and condition i.e. "short and fat" vs. "tall and lean". Barash et al. (1994) reported that heifers fed in a "stair-step" regime of a restricted followed by a compensatory diet were similar in LWT but shorter in hip height compared with heifers fed to attain a constant 0.65 kg/d of LWT gain at the completion of the compensatory period. It was concluded that the "stair-step" fed heifers were using energy for fat gain rather than lean-tissue gain (Barash et al. 1994), and hence were "shorter and fatter" than their constant growth rate contemporaries at similar LWT. It is hypothesised that heifers included in this thesis that were similar in LWT at 21 months of age but did a lesser proportion of their growth in their first year of life (lesser pctLWT21) would have a smaller frame size compared with heifers that did a greater proportion of their growth in their first year. Hence heifers that were a lesser pctLWT21 may have been “shorter and fatter” than heifers that were a greater pctLWT21 that may have been “taller and leaner”. If this was the case, heifers with greater frame size would likely have a greater feed-intake capacity compared with smaller heifers and hence be able to consume more feed during first lactation for milk production (Roche et al. 2015). Results from Chapter 7, where there was a 3% difference in pctLWT21 (59.2% vs 56.3% for Target and Seasonal, respectively) did not result in a difference in girth circumference or wither-to-rump length at 21 months of age, or BCS prior to first calving. It is possible that a greater difference in pctLWT21 may invoke a difference in frame size.

Growing heifers to be heavier would require more feed and would likely be more expensive than the current situation, therefore, the return from milk production and earliness of calving and survival needs to be large enough to make it economically worthwhile for the farmer. It is beyond the scope of this thesis to provide detailed economic analysis; however, a brief estimation of the return from milksolids production has been completed. Currently the mean LWT at three and 15 months of age for FJ heifers is 88.5 and 301.5 kg, respectively (Chapter 3), which equates to a mean growth rate of 0.58 kg/day. To lift a FJ heifer into the “green” zone, a growth rate of between 0.72 kg/day to 0.86 kg/d from three to 15 months of age would be required to reach 350 or 402 kg, respectively. The increased milksolids production of a 350 kg heifer compared with a 301.5 kg heifer was 27.7 kg in first lactation, worth $118.07, based on $6.06 per kg protein and $2.85 per kg fat (DairyNZ 2018d) and 0.56 kg fat and 0.44 kg protein per kg of milksolids (Livestock Improvement Corporation & DairyNZ 2018). The increased milksolids production of a 402 kg heifer compared with 301.5 kg heifer was 52.8 kg in first lactation, worth $224.93. A more detailed and thorough economic analysis could and should be completed based on the findings from this thesis in order to provide “economic-“ or “profit-based” target LWTs.

As discussed in Chapter 2, common biological growth models for animals require an asymptote of mature LWT (e.g. Brody, von Bertalanffy, and Gompertz). For the industry dataset from Chapter 2, only 7% (n=13,662) of the 189,936 heifers had at least one LWT record after first calving. For the experiment described in Chapter 7, (due to time constraints of the PhD programme) heifers were only monitored until the end of first lactation. Mature LWT is reported to be reached between five and eight years of age (DairyNZ 2015a; NZAEL 2012). Hence all LWT records included in this thesis were measured while heifers were still in the ascending growth stage, with no information on mature LWT. If sufficient LWT records were available throughout the lifetime of the heifers included in the thesis, then a more traditional growth model could be appropriate to estimate mature LWT, in addition to the mathematical approach used for growth up to first calving. This would enable further understanding of mature LWT, time to maturity and maturing rate differences among breeds. In addition, the effect of LWT as a proportion of mature LWT on milk production and reproductive performance could have been completed, providing further information on “optimum” LWT and growth trajectories to yield maximum performance of heifers.

Cows that are genetically heavier are more likely to have superior milk production than genetically lighter cows due to the positive genetic correlations between LWT and milk production (Ahlborn & Dempfle 1992; Pryce & Harris 2006). The estimation of LWT (and milk production) BVs for New Zealand dairy cattle includes breed in the statistical model (DairyNZ 2016a). Additionally, breed and LWT BV is expected to be confounded as the mean LWT and volume BVs of Friesian bulls (46.2 kg and 767 kg, respectively) are greater than the mean LWT and volume BVs of Jersey bulls (-53.2 kg and -475 kg, respectively) (Livestock Improvement Corporation & DairyNZ 2018). As outlined in the foreword for Chapter 3, breed and LWT is confounded, therefore, a complicated relationship of breed, LWT and genetic merit for LWT and milk production exists. In this thesis, the confounding between breed and LWT has been controlled for by the stratification of breed in the analyses. However, genetic merit could not be controlled for in the same models as breed and LWT have. The results from this thesis has demonstrated that an increase in LWT, within each breed group prior to first calving had a positive impact on milk production, however, it was not clear whether this impact was due to the positive genetic correlations between LWT and milk production or due to the heifers being phenotypically heavier. In other words, were the heavier and better producing heifers superior to the lighter heifers because they had superior genetics for LWT and milk production or because they were better grown (same genetic potential for LWT and milk production) than the lighter heifers.

8.5.1 Suggested experiment – effects of LWT irrespective of breed and genetic effects

Based on the results from this thesis there are a multitude of options to design an experiment to examine the effects of LWT on milk production and reproduction irrespective of breed and genetic effects. When designing one such experiment equal numbers of heifers that were purebred F, purebred J and first-cross FxJ and the application of growth/LWT treatments within each of these breed groups would be required. The sires used to generate the heifers would need to be balanced for BVs for LWT, milk production (fat, protein and volume), BCS and fertility within each sire breed (F sires for F and FxJ or J sires for J and FxJ breed groups). Additionally, the dams used to generate the heifers would also need to be well-recorded (including LWT records during lactation) and balanced for the same BVs. By balancing the sires and the dams for these BVs within each breed, the effects of LWT on milk production and reproduction can be estimated without the confounding effects of breed and genetic merit.

As outlined earlier there are a multitude of options for potential LWT treatments based on the findings of this thesis; to be concise, four of the potential treatments (per breed group) will be proposed in this section. Growing heifers to be "big" at 21 months of age within their breed group would be the end-point of the experiment, with heifers being balanced for birth weight; i.e. start and end at similar LWT. The three key ages with an ideal LWT range (green zone) identified was six, 12 and 15 months of age (Table 8.1). Treatment A would consist of heifers remaining within this "green zone" of the ideal range at each age. Treatment B would consist of heifers grown to be within the "orange zone" at six months of age followed by the "green zone" at 12 and 15 months of age. Likewise, treatment C would consist of heifers remaining within this "green zone" of the ideal range at six and 15 months of age but falling into the "orange zone" at 12 months of age and treatment D would consist of heifers remaining within this "green zone" of the ideal range at six and 12 months of age but falling into the "orange zone" at 15 months of age. For J heifers, the "orange zone" would need to be replaced with the upper end of the "red zone" due to the narrow range identified for good reproductive performance of J heifers (Table 8.1).

Heifers would be followed until mature LWT was attained (five to eight years of age) and measurements would need to include; LWT, stature (wither height and length), BCS, age at puberty, first lactation milk production, three-parity and lifetime accumulated milk production, stayability, six-week pregnancy rates, 21-day calving rates and the income and costs involved for each rearing treatment. Furthermore, the relationship between LWT BV as a heifer and actual mature LWT recorded could be estimated. For the four mentioned treatments, the hypothesis would be that all treatments would have similar stayability and 21-day calving rates but those that dropped into the “orange zone” would have lower milk yields in first lactation and accumulated three-parity production compared with those that remained in the “green zone”. The number of heifers required would depend on the LWT treatments imposed in the experiment. Therefore, based on the hypothesis that stayability to third calving would be noninferior for heifers in the orange compared with the green zone, the number of heifers required would be 285 per treatment. This is based on the assumptions that stayability to third calving would be 64% and similar for orange or green treatments and that an acceptable difference between the two groups would be 10% (α=0.05; β=0.20).

8.6 Conclusions

There were clear advantages of having heifers heavier through the precalving rearing phase (three to 21 months of age), with the greatest advantage seen by increasing LWT of the lightest heifers. These advantages were consistent across the five breed groups studied and enables the identification of breed specific LWTs to yield maximal performance. The effects of growth pattern on reproduction and milk production were less clear. Results from the prospective experiment indicated there was no lasting effects of a small difference in growth trajectory, results from retrospective studies indicated that there were positive effects of pctLWT21 on milk production and stayability (favouring faster growing heifers) and negative effects on calving rate (favouring slower growing heifers). The performance-based target LWT ranges suggested in this thesis for good reproductive performance and milk production of dairy heifers are heavier than the current industry target LWTs. This indicates that the current estimates of mature LWT are too low and/or that the current target LWTs are too low to achieve the best heifer performance. A thorough economic analysis needs to be completed to provide “economic-” or “profit-” based target LWTs for New Zealand dairy heifers. Overall, these are important findings that can be used to develop guidelines which may improve productivity and survival of dairy cattle in New Zealand.

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Appendices

Appendix I

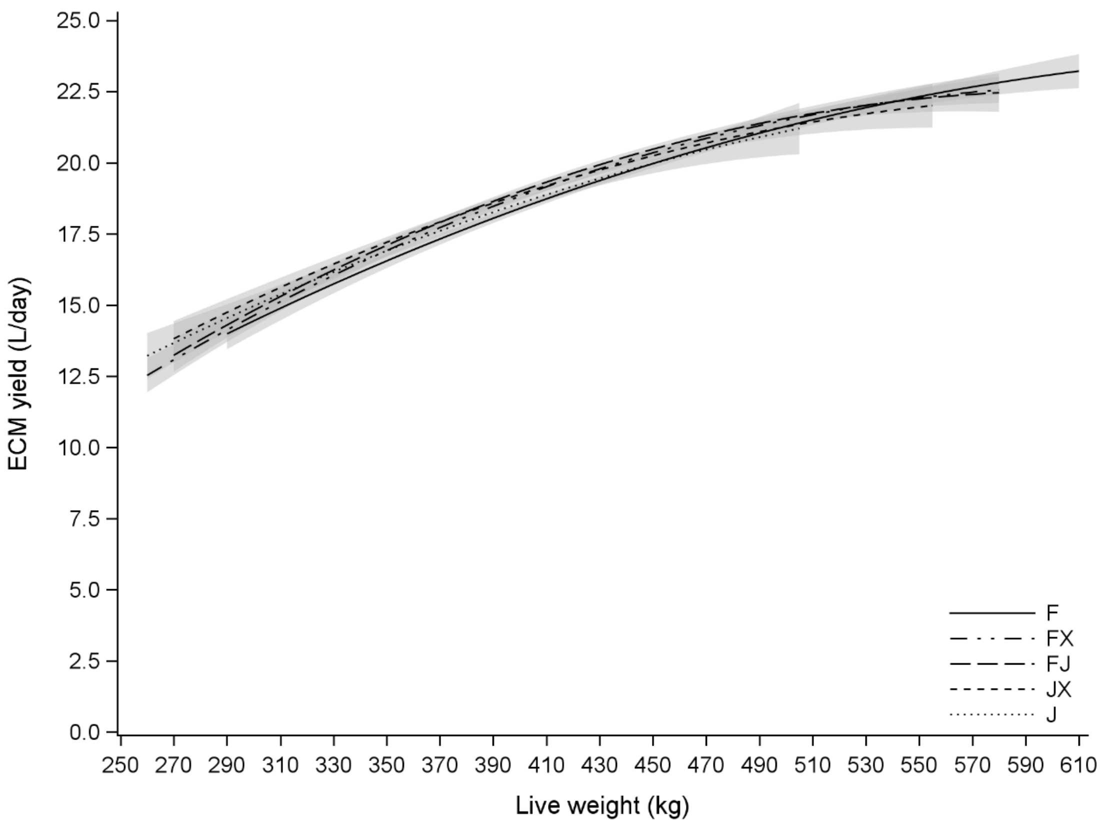
Appendix I. Table 1. Prediction accuracy of the fourth-order Legendre polynomial for the prediction of liveweight of dairy heifers for the Order4-clean, by age, in months.

Age (mo)	N records	Mean Actual (A) kg	Mean Pred (P) kg	Regression of A upon P			Bias (P-A) kg	MSPE kg^2	Proportion of MSPE			MPE (kg)	RPE (%)
				Intercept	Slope	R^2			Mean bias	Line bias	Random		
0	1,315	33.7	28.2	14.085	0.695	0.683	-5.494	50.7	0.596	0.118	0.286	7.1	21.14
1	8,011	52.8	49.2	8.406	0.902	0.831	-3.587	32.2	0.399	0.033	0.568	5.7	10.74
2	49,478	71.9	70.4	8.404	0.902	0.882	-1.517	20.9	0.110	0.072	0.818	4.6	6.36
3	86,968	92.4	92.7	2.862	0.965	0.914	0.377	18.5	0.008	0.014	0.979	4.3	4.65
4	105,021	112.1	113.4	3.767	0.955	0.911	1.300	25.9	0.065	0.021	0.914	5.1	4.54
5	89,950	131.0	133.8	1.998	0.964	0.911	2.864	41.9	0.196	0.012	0.793	6.5	4.94
6	93,191	149.3	150.5	-2.719	1.010	0.922	1.185	40.4	0.035	0.001	0.964	6.4	4.26
7	95,194	169.1	166.4	-5.684	1.050	0.930	-2.703	54.2	0.135	0.026	0.839	7.4	4.35
8	88,513	185.0	180.7	-8.403	1.070	0.926	-4.301	80.1	0.231	0.039	0.730	9.0	4.84
9	97,671	196.8	193.9	-12.342	1.079	0.923	-2.956	84.6	0.103	0.054	0.843	9.2	4.67
10	79,682	207.5	207.0	-13.455	1.067	0.923	-0.478	85.4	0.003	0.045	0.952	9.2	4.45
11	72,155	221.1	223.8	-15.575	1.058	0.937	2.706	83.9	0.087	0.038	0.875	9.2	4.14
12	73,675	236.9	241.7	-16.659	1.049	0.940	4.823	102.4	0.227	0.026	0.747	10.1	4.27
13	105,826	257.4	262.0	-16.463	1.046	0.940	4.528	102.9	0.199	0.023	0.778	10.1	3.94
14	104,317	281.2	282.1	-13.004	1.043	0.946	0.924	85.7	0.010	0.028	0.962	9.3	3.29
15	57,606	313.1	308.6	-7.022	1.037	0.948	-4.495	107.5	0.188	0.019	0.793	10.4	3.31
16	64,538	338.5	332.5	-1.001	1.021	0.950	-5.969	119.9	0.297	0.006	0.697	11.0	3.24
17	68,330	360.7	357.9	-1.997	1.013	0.956	-2.794	83.7	0.093	0.003	0.903	9.2	2.54
18	72,288	378.7	378.8	-5.596	1.015	0.962	0.050	72.0	0.000	0.005	0.995	8.5	2.24
19	66,688	396.8	398.6	-15.496	1.034	0.963	1.798	83.9	0.039	0.027	0.935	9.2	2.31
20	64,190	412.7	414.8	-37.388	1.085	0.969	2.040	86.4	0.048	0.154	0.798	9.3	2.25
21	67,131	421.8	422.6	-46.760	1.109	0.980	0.805	76.1	0.009	0.318	0.673	8.7	2.07
22	26,398	427.3	426.9	-33.788	1.080	0.979	-0.473	78.1	0.003	0.204	0.794	8.8	2.07
23	12,338	440.9	437.9	-15.424	1.042	0.973	-2.991	105.2	0.085	0.051	0.864	10.3	2.33
24	2,740	440.6	436.9	-12.957	1.038	0.870	-3.678	696.5	0.019	0.009	0.972	26.4	5.99

Appendix II

Appendix II. Table 1. Intercept and regression coefficients ± s.e. for the linear and quadratic effects of 21-month live weight (LWT) of dairy heifers on accumulated three-parity energy-corrected milk (ECM) yield per day of lactation

Breed group	Intercept (kg ECM)	P value	Linear (kg ECM per day/kg LWT)	P value	Quadratic (kg ECM per day/kg LWT^2)	P value
F	-3.85 ± 2.12	0.069	0.077 ± 0.009	<0.001	-0.00005 ± 0.00001	<0.001
FX	-7.04 ± 1.85	0.001	0.095 ± 0.009	<0.001	-0.00008 ± 0.00001	<0.001
FJ	-7.43 ± 2.21	0.001	0.098 ± 0.011	<0.001	-0.00008 ± 0.00001	<0.001
JX	-3.93 ± 2.75	0.154	0.084 ± 0.014	<0.001	-0.00007 ± 0.00002	<0.001
J	-2.39 ± 3.97	0.547	0.074 ± 0.021	<0.001	-0.00005 ± 0.00003	0.051



Appendix II. Figure 1. The relationship between live weight at 21 months of age and energy-corrected milk (ECM) yield per day for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) and Jersey (J) heifers. The body weight range for each breed group is the range of body weights observed for that breed group. Grey shading indicates 95% confidence intervals.

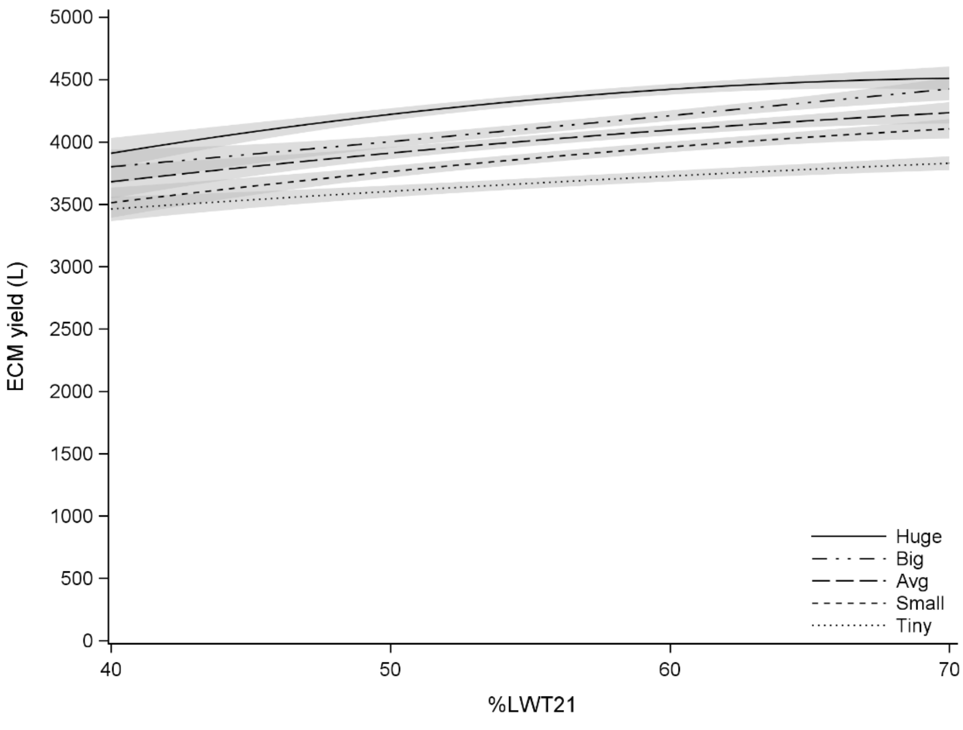
Appendix III

Appendix III includes the tables of absolute growth rate (AGR) from three to 21 months of age for heifers that were tiny, small, average, big or huge at 21 months of age and were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21) for all five breed groups studied in Chapter 4. Additionally, figures illustrating the relationships between pctLWT21 and energy-corrected milk (ECM) yield in first lactation for F, FX, JX and J heifers are also included.

Appendix III. Table 1. Predicted absolute growth rate (AGR; ±SEM) from three to 21 months of age for Holstein-Friesian (F) heifers that were tiny, small, average, big or huge at 21 months of age and were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

	3-6 mo	6-9 mo	9-12 mo	12-15 mo	15-18 mo	18-21 mo
Tiny						
45%	$0.47^{a} \pm 0.003$	$0.22^{a} \pm 0.002$	$0.40^{a} \pm 0.002$	$0.73^{c} \pm 0.002$	$0.94^{c} \pm 0.001$	$0.73^{c} \pm 0.003$
55%	$0.58^{b} \pm 0.002$	$0.39^{b} \pm 0.001$	$0.49^{b} \pm 0.002$	$0.67^{b} \pm 0.002$	$0.75^{b} \pm 0.001$	$0.53^{b} \pm 0.002$
65%	$0.68^{c} \pm 0.002$	$0.56^{c} \pm 0.002$	$0.57^{c} \pm 0.002$	$0.61^{a} \pm 0.002$	$0.57^{a} \pm 0.001$	$0.33^{a} \pm 0.002$
Small						
45%	$0.51^{a} \pm 0.003$	$0.22^{a} \pm 0.002$	$0.43^{a} \pm 0.002$	$0.81^{c} \pm 0.002$	$1.02^{c} \pm 0.001$	$0.75^{c} \pm 0.003$
55%	$0.63^{b} \pm 0.002$	$0.41^{b} \pm 0.001$	$0.53^{b} \pm 0.002$	$0.75^{b} \pm 0.002$	$0.83^{b} \pm 0.001$	$0.53^{b} \pm 0.002$
65%	$0.75^{c} \pm 0.003$	$0.60^{c} \pm 0.002$	$0.63^{c} \pm 0.002$	$0.69^{a} \pm 0.002$	$0.63^{a} \pm 0.001$	$0.30^{a} \pm 0.002$
Average						
45%	$0.53^{a} \pm 0.003$	$0.22^{a} \pm 0.002$	$0.45^{a} \pm 0.002$	$0.86^{c} \pm 0.002$	$1.08^{c} \pm 0.001$	$0.75^{c} \pm 0.003$
55%	$0.66^{b} \pm 0.002$	$0.42^{b} \pm 0.001$	$0.55^{b} \pm 0.002$	$0.79^{b} \pm 0.002$	$0.87^{b} \pm 0.001$	$0.52^{b} \pm 0.002$
65%	$0.79^{c} \pm 0.003$	$0.61^{c} \pm 0.002$	$0.65^{c} \pm 0.002$	$0.73^{a} \pm 0.002$	$0.67^{a} \pm 0.001$	$0.29^{a} \pm 0.003$
Big						
45%	$0.56^{a} \pm 0.003$	$0.22^{a} \pm 0.002$	$0.47^{a} \pm 0.002$	$0.91^{c} \pm 0.002$	$1.13^{c} \pm 0.001$	$0.75^{c} \pm 0.003$
55%	$0.69^{b} \pm 0.002$	$0.43^{b} \pm 0.001$	$0.58^{b} \pm 0.002$	$0.84^{b} \pm 0.002$	$0.92^{b} \pm 0.001$	$0.51^{b} \pm 0.002$
65%	$0.83^{c} \pm 0.003$	$0.63^{c} \pm 0.002$	$0.68^{c} \pm 0.002$	$0.77^{a} \pm 0.002$	$0.71^{a} \pm 0.001$	$0.28^{a} \pm 0.003$
Huge						
45%	$0.61^{a} \pm 0.003$	$0.24^{a} \pm 0.002$	$0.51^{a} \pm 0.003$	$0.98^{c} \pm 0.002$	$1.22^{c} \pm 0.001$	$0.80^{c} \pm 0.003$
55%	$0.75^{b} \pm 0.002$	$0.46^{b} \pm 0.002$	$0.62^{b} \pm 0.002$	$0.90^{b} \pm 0.002$	$0.99^{b} \pm 0.001$	$0.54^{b} \pm 0.002$
65%	$0.89^{c} \pm 0.003$	$0.67^{c} \pm 0.002$	$0.73^{c} \pm 0.002$	$0.83^{a} \pm 0.002$	$0.76^{a} \pm 0.001$	$0.27^{a} \pm 0.003$

[a-c] Values within a column and LWT category with different superscripts differ at the 95% confidence interval.

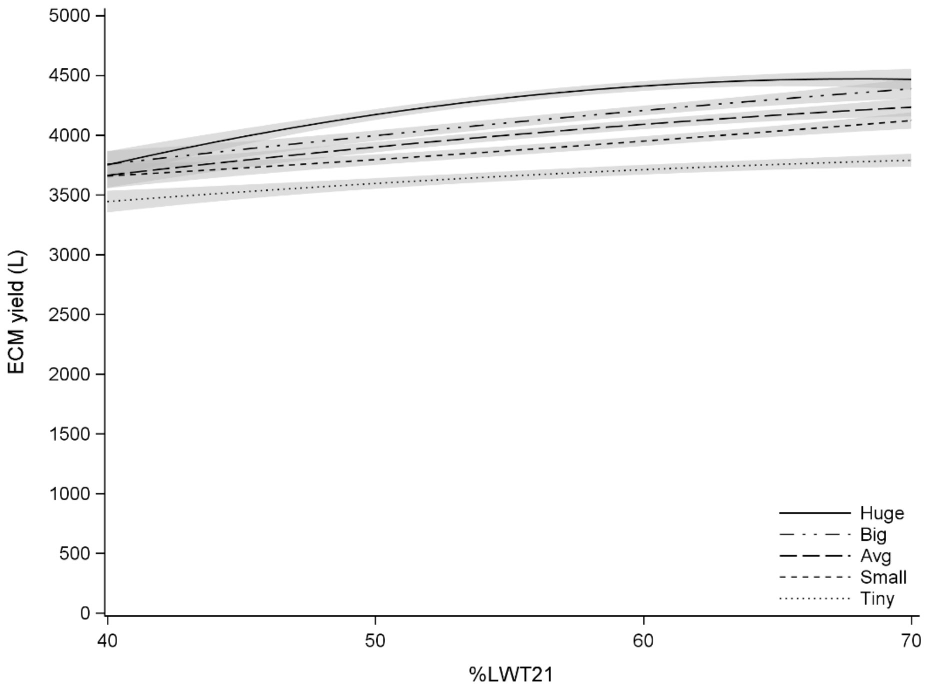


Appendix III. Figure 1. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and first lactation energy-corrected milk (ECM) production for Holstein-Friesian (F) heifers that were tiny, small, average, big or huge at 21 months of age. Shaded area indicates 95% confidence intervals.

Appendix III. Table 2. Predicted absolute growth rate (AGR; ±SEM) from three to 21 months of age for Holstein-Friesian crossbred (FX) heifers that were tiny, small, average, big or huge at 21 months of age and were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

	3-6 mo	6-9 mo	9-12 mo	12-15 mo	15-18 mo	18-21 mo
Tiny						
45%	$0.45^{a} \pm 0.003$	$0.22^{a} \pm 0.002$	$0.39^{a} \pm 0.002$	$0.70^{c} \pm 0.002$	$0.90^{c} \pm 0.001$	$0.74^{c} \pm 0.003$
55%	$0.56^{b} \pm 0.002$	$0.38^{b} \pm 0.001$	$0.47^{b} \pm 0.002$	$0.64^{b} \pm 0.002$	$0.73^{b} \pm 0.001$	$0.53^{b} \pm 0.002$
65%	$0.67^{c} \pm 0.002$	$0.55^{c} \pm 0.002$	$0.55^{c} \pm 0.002$	$0.59^{a} \pm 0.002$	$0.55^{a} \pm 0.001$	$0.33^{a} \pm 0.002$
Small						
45%	$0.49^{a} \pm 0.003$	$0.23^{a} \pm 0.002$	$0.42^{a} \pm 0.002$	$0.77^{c} \pm 0.002$	$0.98^{c} \pm 0.001$	$0.76^{c} \pm 0.003$
55%	$0.62^{b} \pm 0.002$	$0.40^{b} \pm 0.001$	$0.51^{b} \pm 0.002$	$0.71^{b} \pm 0.002$	$0.79^{b} \pm 0.001$	$0.54^{b} \pm 0.002$
65%	$0.74^{c} \pm 0.002$	$0.58^{c} \pm 0.002$	$0.60^{c} \pm 0.002$	$0.65^{a} \pm 0.002$	$0.60^{a} \pm 0.001$	$0.32^{a} \pm 0.002$
Average						
45%	$0.52^{a} \pm 0.003$	$0.22^{a} \pm 0.002$	$0.43^{a} \pm 0.002$	$0.81^{c} \pm 0.002$	$1.04^{c} \pm 0.001$	$0.76^{c} \pm 0.003$
55%	$0.65^{b} \pm 0.002$	$0.41^{b} \pm 0.001$	$0.53^{b} \pm 0.002$	$0.75^{b} \pm 0.002$	$0.84^{b} \pm 0.001$	$0.53^{b} \pm 0.002$
65%	$0.77^{c} \pm 0.002$	$0.60^{c} \pm 0.002$	$0.63^{c} \pm 0.002$	$0.69^{a} \pm 0.002$	$0.64^{a} \pm 0.001$	$0.31^{a} \pm 0.002$
Big						
45%	$0.55^{a} \pm 0.003$	$0.22^{a} \pm 0.002$	$0.45^{a} \pm 0.002$	$0.87^{c} \pm 0.002$	$1.09^{c} \pm 0.001$	$0.75^{c} \pm 0.003$
55%	$0.68^{b} \pm 0.002$	$0.42^{b} \pm 0.001$	$0.55^{b} \pm 0.002$	$0.80^{b} \pm 0.002$	$0.88^{b} \pm 0.001$	$0.52^{b} \pm 0.002$
65%	$0.81^{c} \pm 0.003$	$0.62^{c} \pm 0.002$	$0.65^{c} \pm 0.002$	$0.73^{a} \pm 0.002$	$0.67^{a} \pm 0.001$	$0.30^{a} \pm 0.002$
Huge						
45%	$0.60^{a} \pm 0.003$	$0.24^{a} \pm 0.002$	$0.49^{a} \pm 0.002$	$0.94^{c} \pm 0.002$	$1.17^{c} \pm 0.001$	$0.78^{c} \pm 0.003$
55%	$0.74^{b} \pm 0.002$	$0.45^{b} \pm 0.001$	$0.59^{b} \pm 0.002$	$0.86^{b} \pm 0.002$	$0.95^{b} \pm 0.001$	$0.54^{b} \pm 0.002$
65%	$0.87^{c} \pm 0.003$	$0.65^{c} \pm 0.002$	$0.70^{c} \pm 0.002$	$0.79^{a} \pm 0.002$	$0.72^{a} \pm 0.001$	$0.30^{a} \pm 0.003$

[a-c] Values within a column and LWT category with different superscripts differ at the 95% confidence interval.

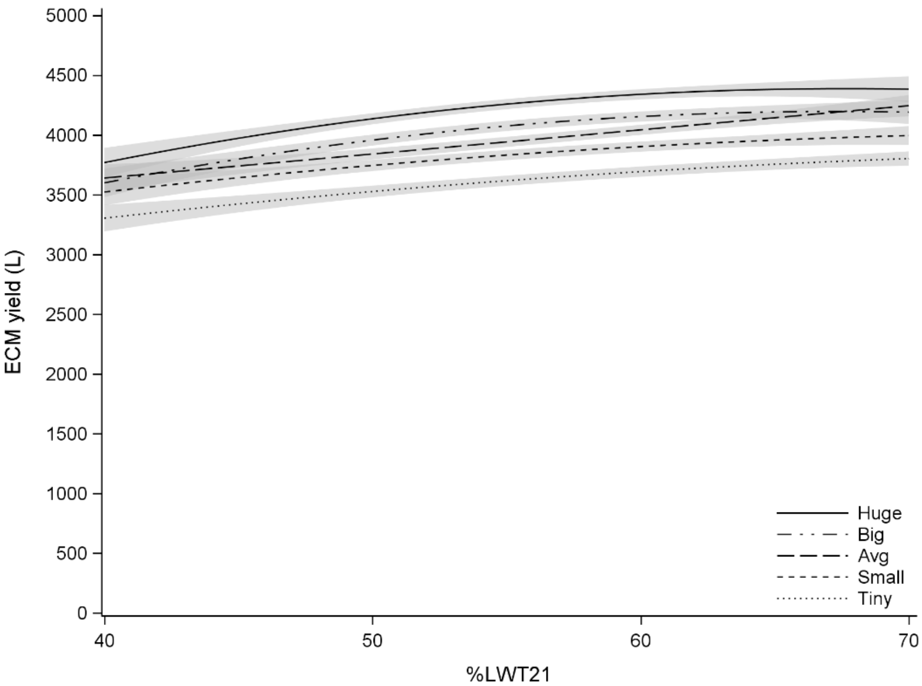


Appendix III. Figure 2. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and first lactation energy-corrected milk (ECM) production for Holstein-Friesian crossbred (FX) heifers that were tiny, small, average, big or huge at 21 months of age. Shaded area indicates 95% confidence intervals.

Appendix III. Table 3. Predicted absolute growth rate (AGR; ±SEM) from three to 21 months of age for Holstein-Friesian-Jersey crossbred (FJ) heifers that were tiny, small, average, big or huge at 21 months of age and were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

	3-6 mo	6-9 mo	9-12 mo	12-15 mo	15-18 mo	18-21 mo
Tiny						
45%	$0.44^{a} \pm 0.003$	$0.22^{a} \pm 0.002$	$0.38^{a} \pm 0.002$	$0.67^{c} \pm 0.002$	$0.87^{c} \pm 0.001$	$0.74^{c} \pm 0.003$
55%	$0.54^{b} \pm 0.002$	$0.38^{b} \pm 0.001$	$0.46^{b} \pm 0.002$	$0.62^{b} \pm 0.002$	$0.70^{b} \pm 0.001$	$0.53^{b} \pm 0.002$
65%	$0.65^{c} \pm 0.002$	$0.53^{c} \pm 0.002$	$0.54^{c} \pm 0.002$	$0.56^{a} \pm 0.002$	$0.53^{a} \pm 0.001$	$0.33^{a} \pm 0.002$
Small						
45%	$0.48^{a} \pm 0.003$	$0.22^{a} \pm 0.002$	$0.40^{a} \pm 0.002$	$0.73^{c} \pm 0.002$	$0.94^{c} \pm 0.001$	$0.76^{c} \pm 0.003$
55%	$0.60^{b} \pm 0.002$	$0.40^{b} \pm 0.001$	$0.49^{b} \pm 0.002$	$0.68^{b} \pm 0.002$	$0.76^{b} \pm 0.001$	$0.54^{b} \pm 0.002$
65%	$0.72^{c} \pm 0.003$	$0.57^{c} \pm 0.002$	$0.58^{c} \pm 0.002$	$0.62^{a} \pm 0.002$	$0.58^{a} \pm 0.001$	$0.33^{a} \pm 0.003$
Average						
45%	$0.51^{a} \pm 0.003$	$0.23^{a} \pm 0.002$	$0.42^{a} \pm 0.002$	$0.78^{c} \pm 0.002$	$0.99^{c} \pm 0.001$	$0.76^{c} \pm 0.003$
55%	$0.63^{b} \pm 0.002$	$0.41^{b} \pm 0.001$	$0.51^{b} \pm 0.002$	$0.72^{b} \pm 0.002$	$0.80^{b} \pm 0.001$	$0.54^{b} \pm 0.002$
65%	$0.75^{c} \pm 0.003$	$0.59^{c} \pm 0.002$	$0.60^{c} \pm 0.002$	$0.66^{a} \pm 0.002$	$0.61^{a} \pm 0.001$	$0.33^{a} \pm 0.003$
Big						
45%	$0.53^{a} \pm 0.003$	$0.23^{a} \pm 0.002$	$0.44^{a} \pm 0.002$	$0.82^{c} \pm 0.002$	$1.05^{c} \pm 0.001$	$0.76^{c} \pm 0.003$
55%	$0.66^{b} \pm 0.002$	$0.42^{b} \pm 0.001$	$0.53^{b} \pm 0.002$	$0.76^{b} \pm 0.002$	$0.85^{b} \pm 0.001$	$0.53^{b} \pm 0.002$
65%	$0.78^{c} \pm 0.003$	$0.61^{c} \pm 0.002$	$0.63^{c} \pm 0.002$	$0.70^{a} \pm 0.002$	$0.64^{a} \pm 0.001$	$0.31^{a} \pm 0.003$
Huge						
45%	$0.58^{a} \pm 0.003$	$0.23^{a} \pm 0.002$	$0.47^{a} \pm 0.002$	$0.90^{c} \pm 0.002$	$1.13^{c} \pm 0.001$	$0.78^{c} \pm 0.003$
55%	$0.71^{b} \pm 0.002$	$0.44^{b} \pm 0.001$	$0.57^{b} \pm 0.002$	$0.82^{b} \pm 0.002$	$0.91^{b} \pm 0.001$	$0.54^{b} \pm 0.002$
65%	$0.84^{c} \pm 0.003$	$0.64^{c} \pm 0.002$	$0.67^{c} \pm 0.002$	$0.75^{a} \pm 0.002$	$0.69^{a} \pm 0.001$	$0.31^{a} \pm 0.003$

[a-c] Values within a column and LWT category with different superscripts differ at the 95% confidence interval.

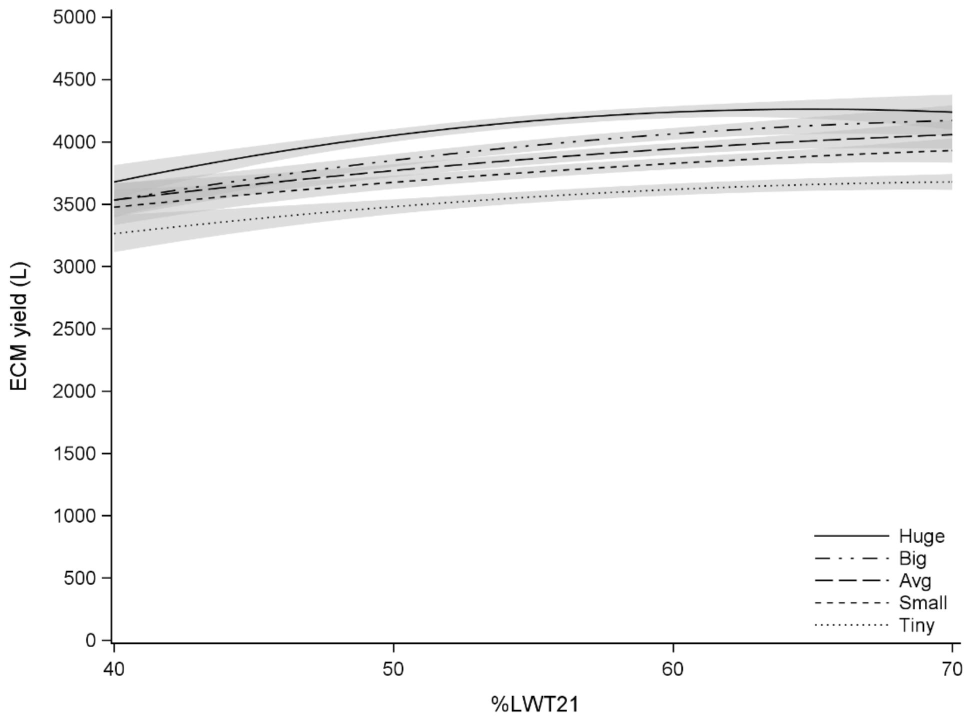


Appendix III. Figure 3. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and first lactation energy-corrected milk (ECM) production for Holstein-Friesian-Jersey crossbred (FJ) heifers that were tiny, small, average, big or huge at 21 months of age. Shaded area indicates 95% confidence intervals.

Appendix III. Table 4. Predicted absolute growth rate (AGR; ±SEM) from three to 21 months of age for Jersey crossbred (JX) heifers that were tiny, small, average, big or huge at 21 months of age and were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

	3-6 mo	6-9 mo	9-12 mo	12-15 mo	15-18 mo	18-21 mo
Tiny						
45%	0.42^{a} ± 0.004	0.22^{a} ± 0.002	0.37^{a} ± 0.003	0.65^{c} ± 0.003	0.84^{c} ± 0.002	0.72^{c} ± 0.004
55%	0.52^{b} ± 0.003	0.37^{b} ± 0.002	0.44^{b} ± 0.002	0.59^{b} ± 0.002	0.67^{b} ± 0.001	0.53^{b} ± 0.002
65%	0.62^{c} ± 0.003	0.52^{c} ± 0.002	0.52^{c} ± 0.002	0.54^{a} ± 0.002	0.50^{a} ± 0.001	0.34^{a} ± 0.003
Small						
45%	0.46^{a} ± 0.003	0.22^{a} ± 0.002	0.38^{a} ± 0.003	0.69^{c} ± 0.003	0.90^{c} ± 0.002	0.76^{c} ± 0.003
55%	0.58^{b} ± 0.002	0.39^{b} ± 0.002	0.47^{b} ± 0.002	0.64^{b} ± 0.002	0.73^{b} ± 0.001	0.55^{b} ± 0.002
65%	0.69^{c} ± 0.003	0.56^{c} ± 0.002	0.56^{c} ± 0.002	0.60^{a} ± 0.002	0.56^{a} ± 0.001	0.33^{a} ± 0.003
Average						
45%	0.49^{a} ± 0.003	0.23^{a} ± 0.002	0.41^{a} ± 0.003	0.74^{c} ± 0.002	0.95^{c} ± 0.001	0.76^{c} ± 0.003
55%	0.61^{b} ± 0.002	0.40^{b} ± 0.002	0.50^{b} ± 0.002	0.68^{b} ± 0.002	0.77^{b} ± 0.001	0.55^{b} ± 0.002
65%	0.73^{c} ± 0.003	0.58^{c} ± 0.002	0.59^{c} ± 0.002	0.63^{a} ± 0.002	0.58^{a} ± 0.001	0.33^{a} ± 0.003
Big						
45%	0.52^{a} ± 0.003	0.23^{a} ± 0.002	0.43^{a} ± 0.003	0.79^{c} ± 0.002	1.00^{c} ± 0.001	0.76^{c} ± 0.003
55%	0.64^{b} ± 0.002	0.41^{b} ± 0.002	0.52^{b} ± 0.002	0.73^{b} ± 0.002	0.81^{b} ± 0.001	0.54^{b} ± 0.002
65%	0.76^{c} ± 0.003	0.60^{c} ± 0.002	0.61^{c} ± 0.002	0.67^{a} ± 0.002	0.62^{a} ± 0.001	0.32^{a} ± 0.003
Huge						
45%	0.57^{a} ± 0.003	0.24^{a} ± 0.002	0.46^{a} ± 0.003	0.86^{c} ± 0.002	1.09^{c} ± 0.001	0.78^{c} ± 0.003
55%	0.70^{b} ± 0.002	0.43^{b} ± 0.002	0.55^{b} ± 0.002	0.79^{b} ± 0.002	0.88^{b} ± 0.001	0.54^{b} ± 0.002
65%	0.82^{c} ± 0.003	0.63^{c} ± 0.002	0.65^{c} ± 0.003	0.72^{a} ± 0.002	0.67^{a} ± 0.001	0.31^{a} ± 0.003

[a-c] Values within a column and LWT category with different superscripts differ at the 95% confidence interval.

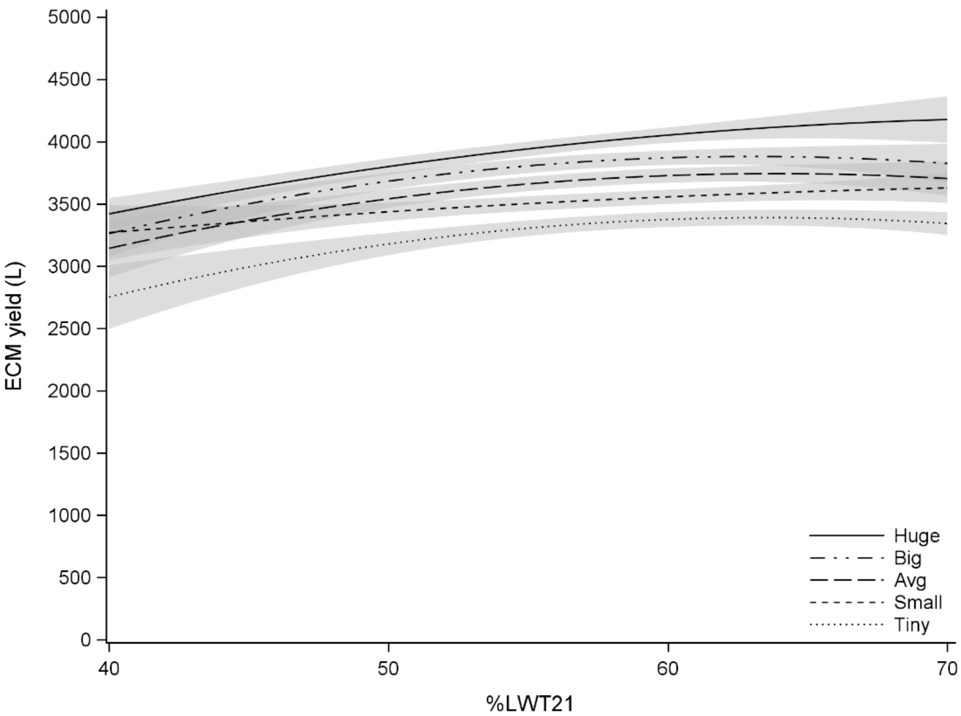


Appendix III. Figure 4. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and first lactation energy-corrected milk (ECM) production for Jersey crossbred (JX) heifers that were tiny, small, average, big or huge at 21 months of age. Shaded area indicates 95% confidence intervals.

Appendix III. Table 5. Predicted absolute growth rate (AGR; ±SEM) from three to 21 months of age for Jersey (J) heifers that were tiny, small, average, big or huge at 21 months of age and were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

	3-6 mo	6-9 mo	9-12 mo	12-15 mo	15-18 mo	18-21 mo
Tiny						
45%	$0.38^{a} \pm 0.005$	$0.22^{a} \pm 0.004$	$0.35^{a} \pm 0.004$	$0.60^{c} \pm 0.004$	$0.77^{c} \pm 0.003$	$0.69^{c} \pm 0.005$
55%	$0.48^{b} \pm 0.003$	$0.36^{b} \pm 0.002$	$0.42^{b} \pm 0.003$	$0.54^{b} \pm 0.002$	$0.61^{b} \pm 0.001$	$0.52^{b} \pm 0.003$
65%	$0.58^{c} \pm 0.003$	$0.50^{c} \pm 0.002$	$0.48^{c} \pm 0.003$	$0.48^{a} \pm 0.003$	$0.45^{a} \pm 0.002$	$0.35^{a} \pm 0.003$
Small						
45%	$0.43^{a} \pm 0.005$	$0.22^{a} \pm 0.003$	$0.36^{a} \pm 0.004$	$0.63^{c} \pm 0.004$	$0.83^{c} \pm 0.002$	$0.75^{c} \pm 0.005$
55%	$0.53^{b} \pm 0.003$	$0.38^{b} \pm 0.002$	$0.44^{b} \pm 0.002$	$0.58^{b} \pm 0.002$	$0.66^{b} \pm 0.001$	$0.55^{b} \pm 0.003$
65%	$0.63^{c} \pm 0.004$	$0.54^{c} \pm 0.002$	$0.53^{c} \pm 0.003$	$0.54^{a} \pm 0.003$	$0.50^{a} \pm 0.002$	$0.35^{a} \pm 0.004$
Average						
45%	$0.46^{a} \pm 0.005$	$0.23^{a} \pm 0.003$	$0.38^{a} \pm 0.004$	$0.67^{c} \pm 0.004$	$0.87^{c} \pm 0.002$	$0.76^{c} \pm 0.005$
55%	$0.57^{b} \pm 0.003$	$0.39^{b} \pm 0.002$	$0.46^{b} \pm 0.002$	$0.62^{b} \pm 0.002$	$0.70^{b} \pm 0.001$	$0.55^{b} \pm 0.003$
65%	$0.68^{c} \pm 0.004$	$0.55^{c} \pm 0.002$	$0.54^{c} \pm 0.003$	$0.57^{a} \pm 0.003$	$0.53^{a} \pm 0.002$	$0.35^{a} \pm 0.004$
Big						
45%	$0.49^{a} \pm 0.004$	$0.23^{a} \pm 0.003$	$0.39^{a} \pm 0.003$	$0.71^{c} \pm 0.003$	$0.93^{c} \pm 0.002$	$0.77^{c} \pm 0.004$
55%	$0.60^{b} \pm 0.003$	$0.40^{b} \pm 0.002$	$0.48^{b} \pm 0.002$	$0.66^{b} \pm 0.002$	$0.74^{b} \pm 0.001$	$0.56^{b} \pm 0.003$
65%	$0.72^{c} \pm 0.004$	$0.58^{c} \pm 0.003$	$0.57^{c} \pm 0.003$	$0.60^{a} \pm 0.003$	$0.56^{a} \pm 0.002$	$0.35^{a} \pm 0.004$
Huge						
45%	$0.53^{a} \pm 0.004$	$0.23^{a} \pm 0.003$	$0.43^{a} \pm 0.003$	$0.80^{c} \pm 0.003$	$1.02^{c} \pm 0.002$	$0.77^{c} \pm 0.004$
55%	$0.65^{b} \pm 0.003$	$0.42^{b} \pm 0.002$	$0.52^{b} \pm 0.002$	$0.73^{b} \pm 0.002$	$0.81^{b} \pm 0.001$	$0.55^{b} \pm 0.003$
65%	$0.77^{c} \pm 0.004$	$0.61^{c} \pm 0.003$	$0.61^{c} \pm 0.003$	$0.66^{a} \pm 0.003$	$0.61^{a} \pm 0.002$	$0.34^{a} \pm 0.004$

$^{a\text{-}c}$ Values within a column and LWT category with different superscripts differ at the 95% confidence interval.



Appendix III. Figure 5. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and first lactation energy-corrected milk (ECM) production for Jersey (J) heifers that were tiny, small, average, big or huge at 21 months of age. Shaded area indicates 95% confidence intervals.

Appendix IV

Appendix IV includes the tables of regression coefficients for the linear and quadratic effects of LWT at six, 12 and 15 months of age on stayability and marginal stayability for all five breed groups studied in Chapter 5. Additionally, figures illustrating the relationships between LWT at 15 months of age and stayability and marginal stayability for F, FX, JX and J heifers are also included.

Appendix IV also includes the tables comparing heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age for stayability and marginal stayability within all five breed groups and five LWT categories studied in Chapter 5.

8.1.1 Stayability

Appendix IV. Table 1. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at six months of age (6m) on stayability (STAY) to calving as a two-year-old; P(C2yo), three-year-old; P(C3yo) or four-year-old; P(C4yo), provided the heifer was reared for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers

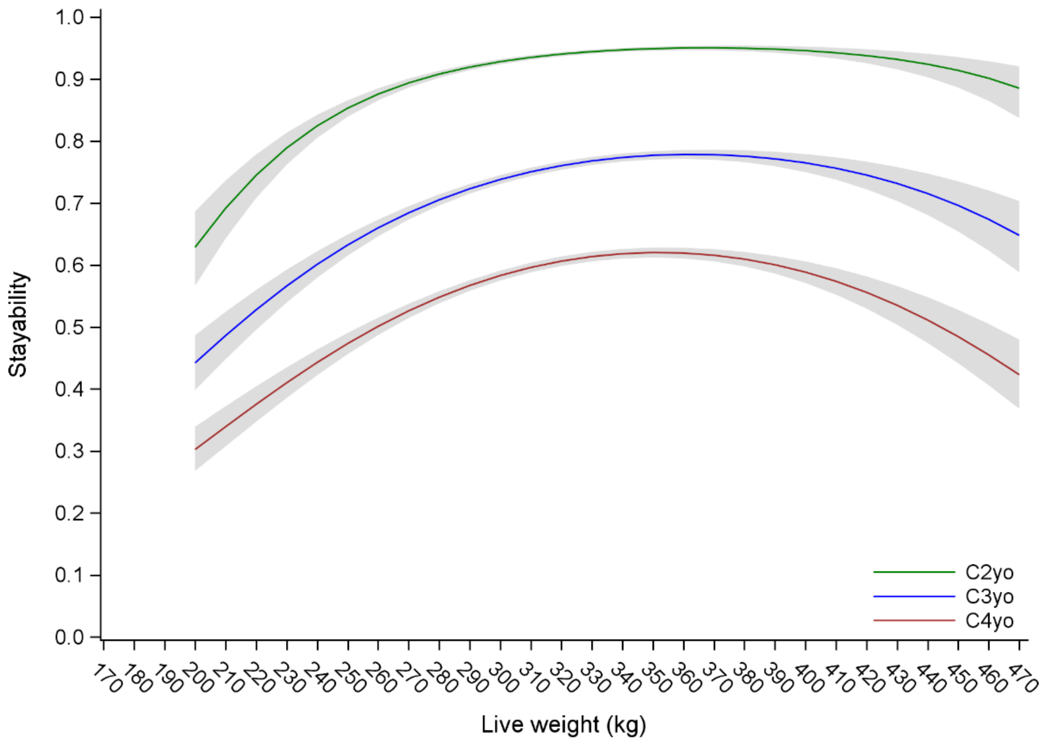
	Intercept	P value	Linear	P value	Quadratic	P value
P(C2yo)						
F	-0.74 ± 0.61	0.222	0.033 ± 0.008	<0.001	-0.00007 ± 0.00002	0.003
FX	-1.58 ± 0.54	0.003	0.046 ± 0.007	<0.001	-0.00011 ± 0.00002	<0.001
FJ	-0.13 ± 0.66	0.839	0.028 ± 0.009	0.002	-0.00007 ± 0.00003	0.026
JX	-0.18 ± 0.84	0.828	0.033 ± 0.012	0.005	-0.00009 ± 0.00004	0.016
J	0.67 ± 1.13	0.555	0.026 ± 0.016	0.113	-0.00010 ± 0.00006	0.093
P(C3yo)						
F	-1.33 ± 0.38	<0.001	0.024 ± 0.005	<0.001	-0.00006 ± 0.00002	<0.001
FX	-1.21 ± 0.35	<0.001	0.026 ± 0.005	<0.001	-0.00006 ± 0.00002	<0.001
FJ	-1.90 ± 0.42	<0.001	0.035 ± 0.006	<0.001	-0.00009 ± 0.00002	<0.001
JX	-1.12 ± 0.54	0.037	0.028 ± 0.007	<0.001	-0.00008 ± 0.00003	<0.001
J	-1.57 ± 0.73	0.031	0.034 ± 0.011	0.001	-0.00011 ± 0.00004	0.004
P(C4yo)						
F	-2.22 ± 0.35	<0.001	0.028 ± 0.004	<0.001	-0.00007 ± 0.00001	<0.001
FX	-1.55 ± 0.31	<0.001	0.022 ± 0.004	<0.001	-0.00006 ± 0.00001	<0.001
FJ	-2.46 ± 0.38	<0.001	0.035 ± 0.005	<0.001	-0.00010 ± 0.00002	<0.001
JX	-1.60 ± 0.48	<0.001	0.026 ± 0.007	<0.001	-0.00008 ± 0.00002	<0.001
J	-1.90 ± 0.66	0.004	0.029 ± 0.010	0.003	-0.00009 ± 0.00004	0.010

Appendix IV. Table 2. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at 12 months of age (12m) on stayability (STAY) to calving as a two-year-old P(C2yo), three-year-old P(C3yo) or four-year-old P(C4yo) provided the heifer was reared for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers

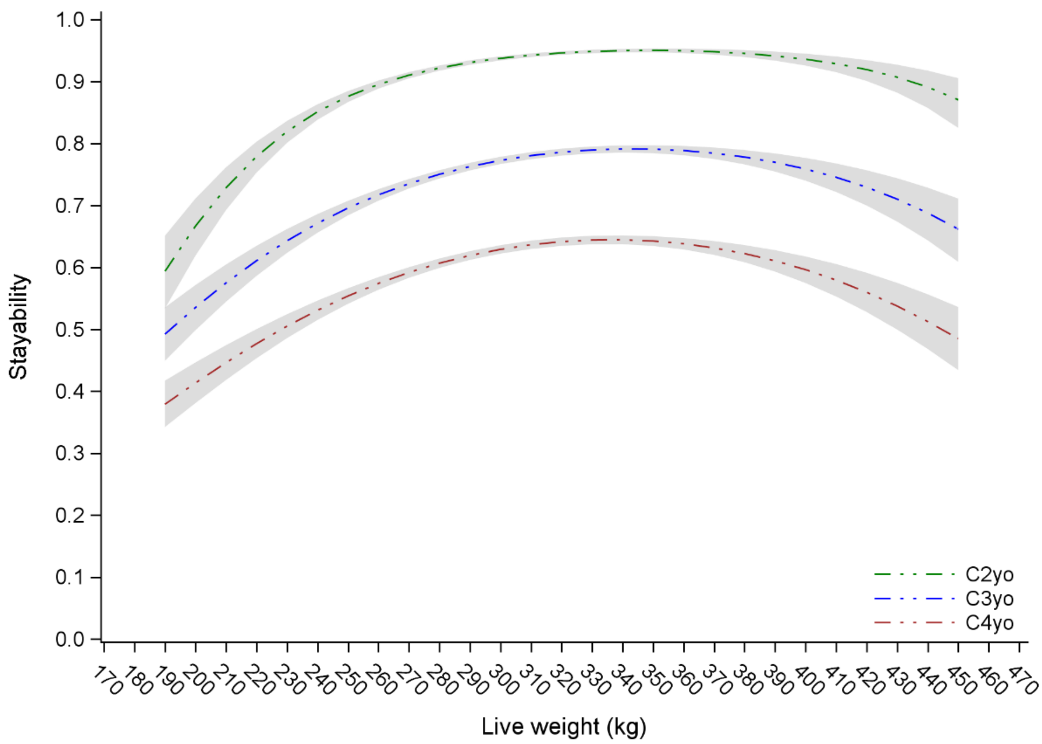
	Intercept	P-value	Linear	P-value	Quadratic	P-value
P(C2yo)						
F	-6.48 ± 0.71	<0.001	0.066 ± 0.006	<0.001	-0.00012 ± 0.00001	<0.001
FX	-6.32 ± 0.65	<0.001	0.067 ± 0.005	<0.001	-0.00012 ± 0.00001	<0.001
FJ	-5.43 ± 0.81	<0.001	0.062 ± 0.007	<0.001	-0.00012 ± 0.00002	<0.001
JX	-5.06 ± 1.08	<0.001	0.062 ± 0.009	<0.001	-0.00012 ± 0.00002	<0.001
J	-2.36 ± 1.63	0.148	0.040 ± 0.015	0.0082	-0.00008 ± 0.00004	0.0165
P(C3yo)						
F	-4.5 ± 0.48	<0.001	0.040 ± 0.004	<0.001	-0.00007 ± 0.00001	<0.001
FX	-3.4 ± 0.45	<0.001	0.034 ± 0.004	<0.001	-0.00006 ± 0.00001	<0.001
FJ	-3.87 ± 0.56	<0.001	0.038 ± 0.005	<0.001	-0.00007 ± 0.00001	<0.001
JX	-4.34 ± 0.74	<0.001	0.045 ± 0.006	<0.001	-0.00009 ± 0.00001	<0.001
J	-4.35 ± 1.1	<0.001	0.045 ± 0.010	<0.001	-0.00009 ± 0.00002	<0.001
P(C4yo)						
F	-5.22 ± 0.45	<0.001	0.041 ± 0.004	<0.001	-0.00007 ± 0.00001	<0.001
FX	-3.39 ± 0.41	<0.001	0.029 ± 0.003	<0.001	-0.00005 ± 0.00001	<0.001
FJ	-3.76 ± 0.51	<0.001	0.033 ± 0.004	<0.001	-0.00006 ± 0.00001	<0.001
JX	-4.36 ± 0.68	<0.001	0.040 ± 0.006	<0.001	-0.00008 ± 0.00001	<0.001
J	-4.93 ± 1.02	<0.001	0.045 ± 0.009	<0.001	-0.00009 ± 0.00002	<0.001

Appendix IV. Table 3. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at 15 months of age (15m) on stayability (STAY) to calving as a two-year-old P(C2yo), three-year-old P(C3yo) or four-year-old P(C4yo) provided the heifer was reared for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers

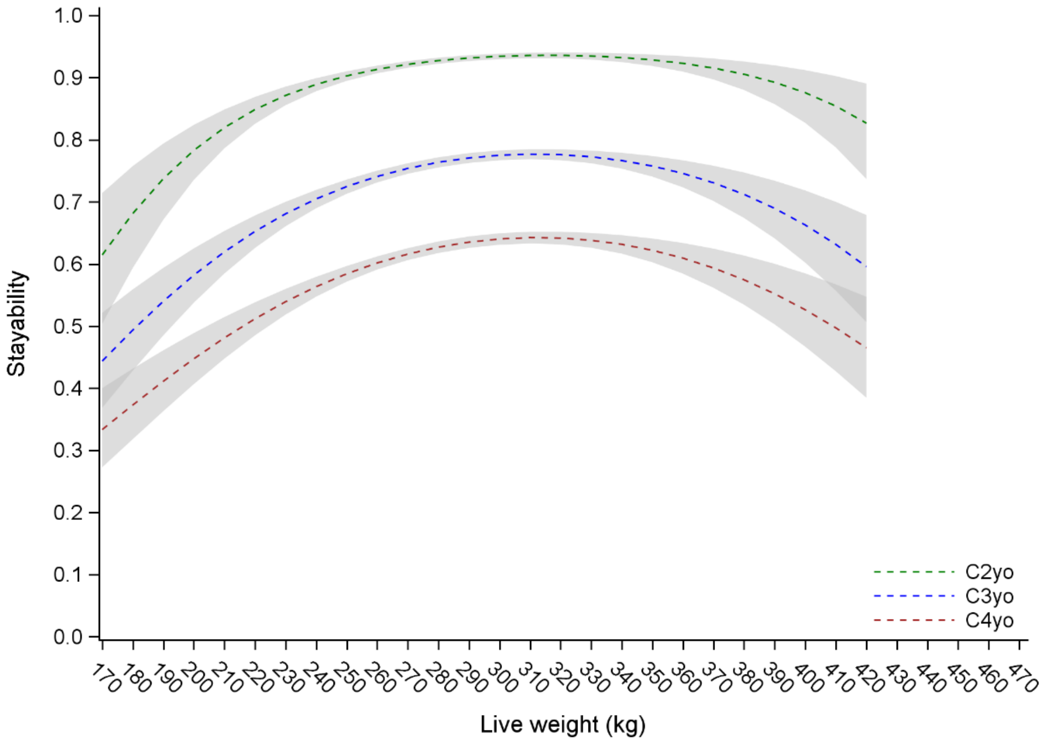
	Intercept	P-value	Linear	P-value	Quadratic	P-value
P(C2yo)						
F	-8.73 ± 0.90	<0.001	0.064 ± 0.006	<0.001	-0.00009 ± 0.00001	<0.001
FX	-9.46 ± 0.82	<0.001	0.071 ± 0.005	<0.001	-0.00010 ± 0.00001	<0.001
FJ	-7.81 ± 1.04	<0.001	0.063 ± 0.007	<0.001	-0.00009 ± 0.00001	<0.001
JX	-7.69 ± 1.32	<0.001	0.066 ± 0.009	<0.001	-0.00010 ± 0.00002	<0.001
J	-4.15 ± 2.01	0.039	0.045 ± 0.015	0.002	-0.00008 ± 0.00003	0.004
P(C3yo)						
F	-6.14 ± 0.61	<0.001	0.041 ± 0.004	<0.001	-0.00006 ± 0.00001	<0.001
FX	-5.50 ± 0.57	<0.001	0.040 ± 0.004	<0.001	-0.00006 ± 0.00001	<0.001
FJ	-5.63 ± 0.71	<0.001	0.041 ± 0.005	<0.001	-0.00006 ± 0.00001	<0.001
JX	-5.88 ± 0.91	<0.001	0.046 ± 0.006	<0.001	-0.00007 ± 0.00001	<0.001
J	-5.83 ± 1.34	<0.001	0.046 ± 0.010	<0.001	-0.00008 ± 0.00002	<0.001
P(C4yo)						
F	-6.62 ± 0.57	<0.001	0.040 ± 0.004	<0.001	-0.00006 ± 0.00001	<0.001
FX	-5.15 ± 0.52	<0.001	0.034 ± 0.003	<0.001	-0.00005 ± 0.00001	<0.001
FJ	-5.18 ± 0.65	<0.001	0.035 ± 0.004	<0.001	-0.00005 ± 0.00001	<0.001
JX	-5.56 ± 0.84	<0.001	0.039 ± 0.006	<0.001	-0.00006 ± 0.00001	<0.001
J	-6.58 ± 1.24	<0.001	0.048 ± 0.009	<0.001	-0.00008 ± 0.00002	<0.001



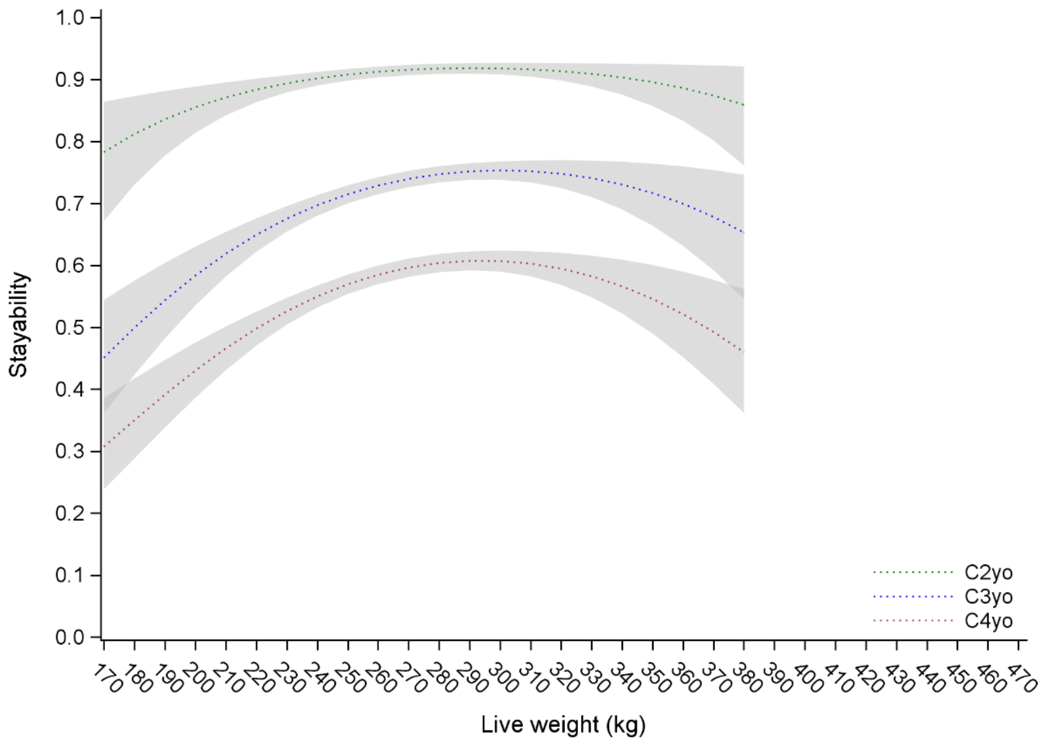
Appendix IV. Figure 1. Relationship between live weight (LWT) at 15 months of age and stayability of Holstein-Friesian (F) heifers that calved as two-year-olds (C2yo), three-year-olds (C3yo) or four-year-olds (C4yo) provided they were reared. Shaded area indicates 95% confidence intervals.



Appendix IV. Figure 2. Relationship between live weight (LWT) at 15 months of age and stayability of Holstein-Friesian crossbred (FX) heifers that calved as two-year-olds (C2yo), three-year-olds (C3yo) or four-year-olds (C4yo) provided they were reared. Shaded area indicates 95% confidence intervals.



Appendix IV. Figure 3. Relationship between live weight (LWT) at 15 months of age and stayability of Jersey crossbred (JX) heifers that calved as two-year-olds (C2yo), three-year-olds (C3yo) or four-year-olds (C4yo) provided they were reared. Shaded area indicates 95% confidence intervals.



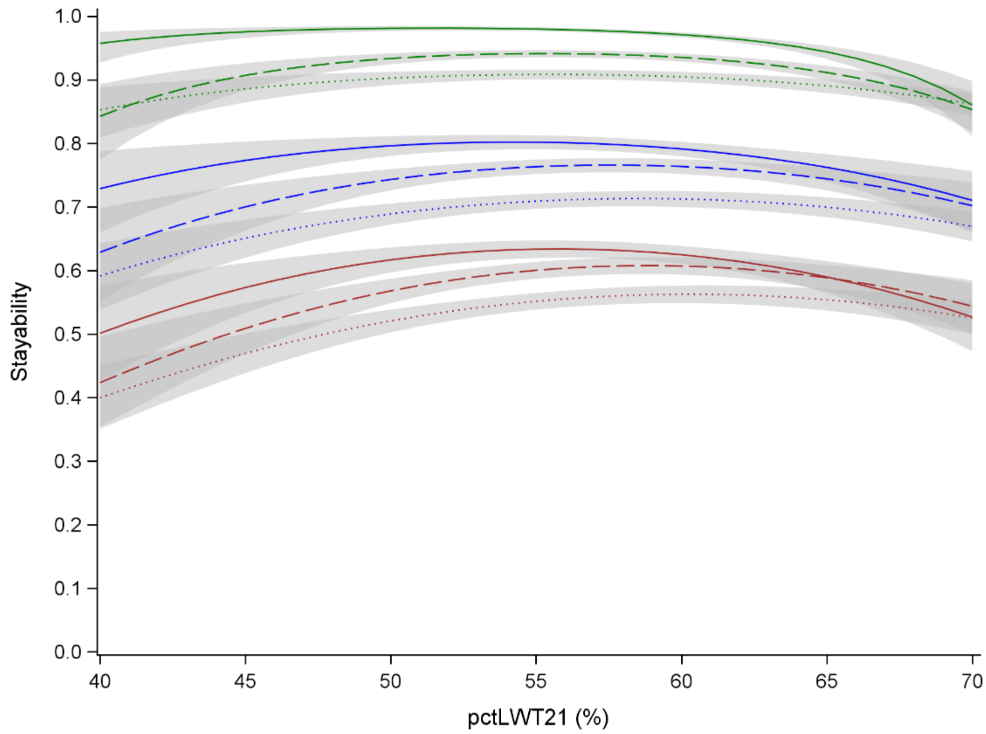
Appendix IV. Figure 4. Relationship between live weight (LWT) at 15 months of age and stayability of Jersey (J) heifers that calved as two-year-olds (C2yo), three-year-olds (C3yo) or four-year-olds (C4yo) provided they were reared. Shaded area indicates 95% confidence intervals.

Appendix IV. Table 4. Least-squares means ± SEM of stayability to calving as a two- (C2yo), three- (C3yo) or four-year-old (C4yo), provided they were reared of heifers that were tiny, small, average, big or huge within breed group at 21 months of age.

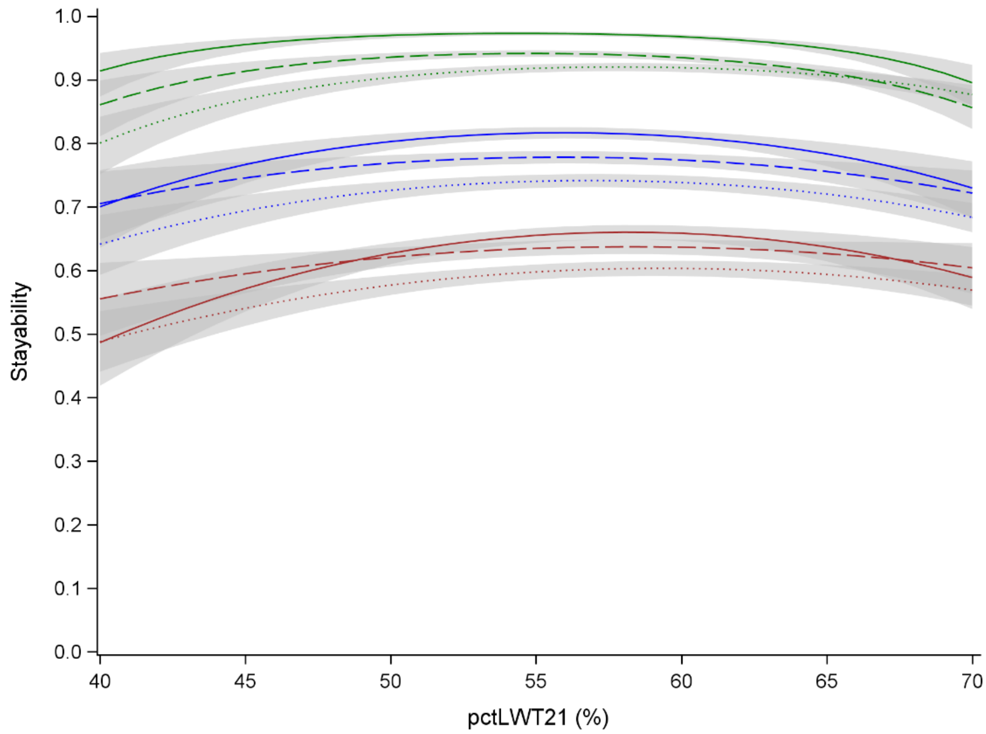
Breed and LWT rank	P(C2yo)	P(C3yo)	P(C4yo)
F			
Tiny	$89.7^{a} \pm 0.4$	$69.8^{a} \pm 0.6$	$54.3^{a} \pm 0.6$
Small	$92.2^{b} \pm 0.3$	$73.6^{b} \pm 0.5$	$58.7^{b} \pm 0.6$
Average	$93.0^{c} \pm 0.3$	$75.3^{c} \pm 0.5$	$59.1^{b} \pm 0.6$
Big	$94.8^{d} \pm 0.2$	$77.3^{d} \pm 0.5$	$62.0^{c} \pm 0.6$
Huge	$97.2^{e} \pm 0.2$	$78.9^{e} \pm 0.5$	$61.8^{c} \pm 0.6$
FX			
Tiny	$90.7^{a} \pm 0.3$	$72.8^{a} \pm 0.5$	$59.1^{a} \pm 0.5$
Small	$92.3^{b} \pm 0.3$	$76.2^{b} \pm 0.4$	$62.0^{b} \pm 0.5$
Average	$93.1^{c} \pm 0.3$	$77.0^{b} \pm 0.4$	$63.0^{b} \pm 0.5$
Big	$94.3^{d} \pm 0.2$	$78.1^{c} \pm 0.4$	$63.2^{c} \pm 0.5$
Huge	$96.7^{e} \pm 0.2$	$80.5^{d} \pm 0.4$	$64.5^{d} \pm 0.5$
FJ			
Tiny	$90.5^{a} \pm 0.4$	$72.7^{a} \pm 0.6$	$59.3^{a} \pm 0.6$
Small	$92.6^{bc} \pm 0.3$	$76.6^{b} \pm 0.5$	$63.7^{b} \pm 0.6$
Average	$92.4^{b} \pm 0.3$	$77.2^{bc} \pm 0.5$	$64.0^{b} \pm 0.6$
Big	$93.3^{c} \pm 0.3$	$78.2^{c} \pm 0.5$	$64.7^{bc} \pm 0.6$
Huge	$95.4^{d} \pm 0.2$	$80.3^{d} \pm 0.5$	$65.6^{c} \pm 0.6$
JX			
Tiny	$90.4^{a} \pm 0.5$	$72.1^{a} \pm 0.7$	$58.6^{a} \pm 0.8$
Small	$92.7^{b} \pm 0.4$	$76.7^{bc} \pm 0.7$	$62.6^{b} \pm 0.8$
Average	$92.7^{b} \pm 0.4$	$77.6^{c} \pm 0.7$	$63.8^{b} \pm 0.8$
Big	$92.0^{b} \pm 0.4$	$75.5^{b} \pm 0.7$	$63.2^{b} \pm 0.8$
Huge	$93.9^{c} \pm 0.3$	$76.8^{bc} \pm 0.7$	$62.2^{b} \pm 0.8$
J			
Tiny	$91.4^{bc} \pm 0.7$	$68.8^{a} \pm 1.2$	$53.4^{a} \pm 1.3$
Small	$92.0^{bc} \pm 0.7$	$74.2^{b} \pm 1.1$	$58.4^{bc} \pm 1.2$
Average	$92.9^{c} \pm 0.6$	$73.6^{b} \pm 1.0$	$60.7^{c} \pm 1.1$
Big	$91.0^{b} \pm 0.7$	$74.4^{b} \pm 1.0$	$59.9^{bc} \pm 1.2$
Huge	$88.6^{a} \pm 0.8$	$71.9^{b} \pm 1.1$	$57.3^{b} \pm 1.2$

$^{a-d}$Values within column and breed group with different superscripts differ between LWT categories (P<0.05).

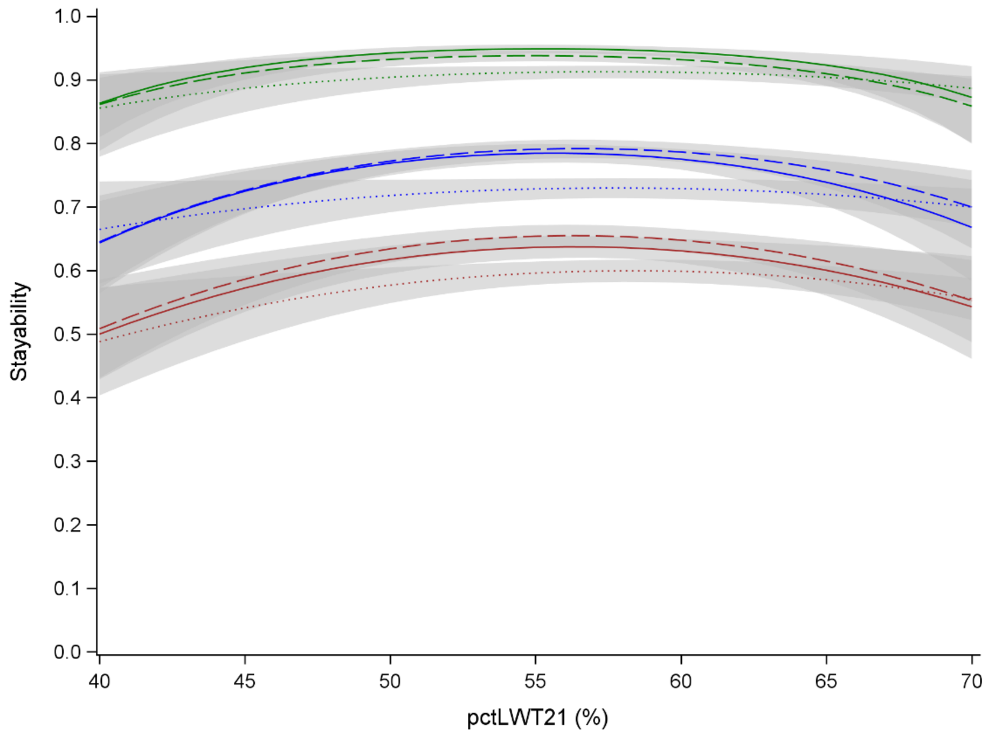
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.



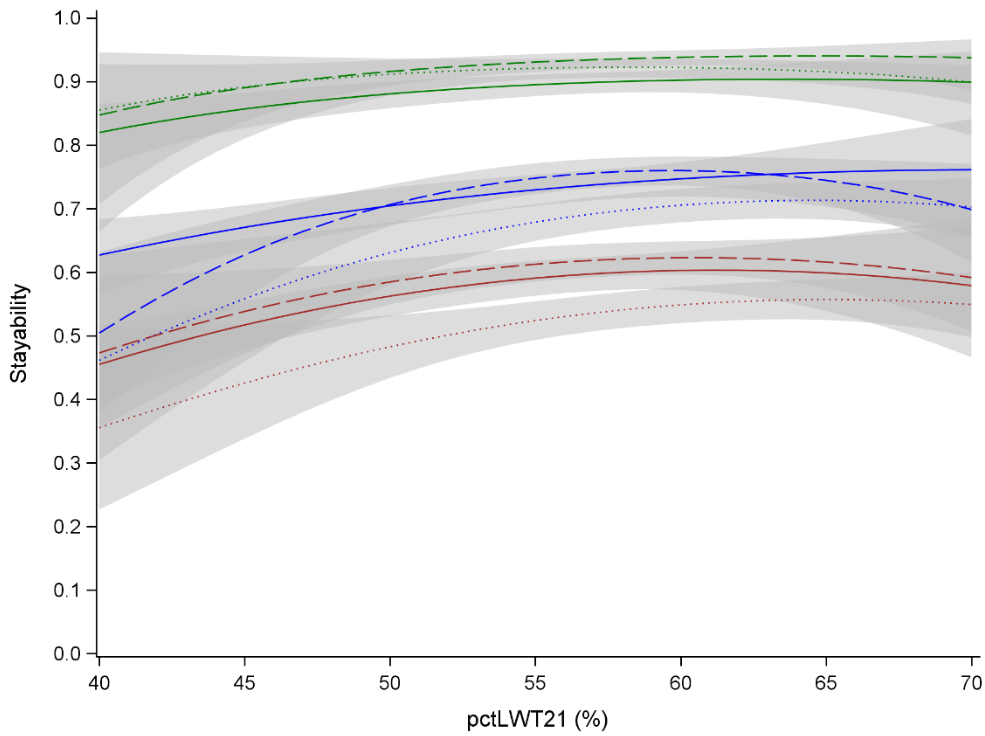
Appendix IV. Figure 5. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and stayability to calving as a two-year-old (C2yo; green lines), three-year-old (C3yo; blue lines) or four-year-old (C4yo; red lines) provided they were reared for Holstein-Friesian (F) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.



Appendix IV. Figure 6. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and stayability to calving as a two-year-old (C2yo; green lines), three-year-old (C3yo; blue lines) or four-year-old (C4yo; red lines) provided they were reared for Holstein-Friesian crossbred (FX) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.



Appendix IV. Figure 7. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and stayability to calving as a two-year-old (C2yo; green lines), three-year-old (C3yo; blue lines) or four-year-old (C4yo; red lines) provided they were reared for Jersey crossbred (JX) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.



Appendix IV. Figure 8. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and stayability to calving as a two-year-old (C2yo; green lines), three-year-old (C3yo; blue lines) or four-year-old (C4yo; red lines) provided they were reared for Jersey (J) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.

Appendix IV. Table 5. Predicted stayability (STAY) ± SEM to calving as two-year-old provided they were reared of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		STAY(C2yo|rear)		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	88.6 ± 1.0	90.8 ± 0.4	89.1 ± 0.5
	Small	87.9^{a} ± 1.1	93.4^{c} ± 0.3	91.1^{b} ± 0.5
	Average	90.7^{a} ± 1.1	94.1^{b} ± 0.3	91.1^{a} ± 0.6
	Big	93.4^{a} ± 0.9	95.7^{b} ± 0.2	93.0^{a} ± 0.5
	Huge	97.6^{b} ± 0.4	98.0^{b} ± 0.2	94.4^{a} ± 0.5
FX				
	Tiny	87.0^{a} ± 1.0	91.8^{b} ± 0.3	90.7^{b} ± 0.4
	Small	87.7^{a} ± 1.0	93.7^{c} ± 0.3	91.1^{b} ± 0.5
	Average	91.4^{a} ± 0.8	94.2^{b} ± 0.3	91.2^{a} ± 0.5
	Big	92.6^{a} ± 0.8	95.2^{b} ± 0.2	92.1^{a} ± 0.5
	Huge	95.5^{a} ± 0.5	97.3^{b} ± 0.2	94.9^{a} ± 0.4
FJ				
	Tiny	87.8^{a} ± 1.2	91.7^{b} ± 0.4	90.1^{b} ± 0.5
	Small	91.0^{a} ± 0.9	93.5^{b} ± 0.3	91.5^{a} ± 0.6
	Average	88.4^{a} ± 1.1	93.5^{b} ± 0.3	91.2^{a} ± 0.7
	Big	90.8^{a} ± 0.9	94.5^{b} ± 0.3	90.6^{a} ± 0.7
	Huge	93.8^{a} ± 0.7	96.3^{b} ± 0.2	93.1^{a} ± 0.7
JX				
	Tiny	88.7 ± 1.7	91.2 ± 0.5	90.4 ± 0.7
	Small	90.1^{a} ± 1.4	93.8^{b} ± 0.4	91.4^{a} ± 0.8
	Average	91.1^{ab} ± 1.1	93.8^{b} ± 0.4	91.0^{a} ± 0.9
	Big	89.2^{a} ± 1.2	92.9^{b} ± 0.4	91.1^{ab} ± 1.0
	Huge	91.9^{a} ± 0.9	94.9^{b} ± 0.4	92.3^{a} ± 1.0
J				
	Tiny	89.1 ± 3.2	92.1 ± 0.8	91.5 ± 0.9
	Small	92.8 ± 2.0	93.1 ± 0.7	90.7 ± 1.1
	Average	89.0 ± 2.2	93.1 ± 0.7	94.0 ± 0.9
	Big	86.7^{a} ± 1.9	90.9^{ab} ± 0.8	93.3^{b} ± 1.1
	Huge	85.7 ± 1.4	89.5 ± 0.9	90.3 ± 1.7

Values within a row with different superscripts differ at the 95% confidence interval. F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix IV. Table 6. Predicted stayability (STAY) ± SEM to calving as three-year-old provided they were reared of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		STAY(C3yo|rear)		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	65.1^{a} ± 1.5	70.9^{b} ± 0.6	70.0^{b} ± 0.8
	Small	63.7^{a} ± 1.7	74.4^{b} ± 0.6	74.6^{b} ± 0.9
	Average	70.0^{a} ± 1.8	76.3^{b} ± 0.6	74.4^{ab} ± 0.9
	Big	69.2^{a} ± 2.0	78.1^{b} ± 0.6	77.0^{b} ± 0.9
	Huge	77.3^{ab} ± 1.6	80.2^{b} ± 0.6	76.2^{a} ± 1.1
FX				
	Tiny	69.4^{a} ± 1.3	74.0^{b} ± 0.5	72.0^{ab} ± 0.7
	Small	69.2^{a} ± 1.4	77.8^{c} ± 0.5	74.5^{b} ± 0.8
	Average	74.6 ± 1.3	77.8 ± 0.5	75.6 ± 0.9
	Big	74.3^{a} ± 1.5	79.1^{b} ± 0.5	76.5^{ab} ± 0.9
	Huge	76.7^{a} ± 1.4	81.6^{b} ± 0.5	78.3^{a} ± 1.0
FJ				
	Tiny	66.5^{a} ± 1.7	73.5^{b} ± 0.6	73.3^{b} ± 0.8
	Small	73.3 ± 1.5	77.2 ± 0.6	76.4 ± 0.9
	Average	69.5^{a} ± 1.5	78.3^{b} ± 0.6	77.2^{b} ± 1.0
	Big	72.7^{a} ± 1.5	79.3^{b} ± 0.6	77.4^{ab} ± 1.1
	Huge	75.3^{a} ± 1.4	81.5^{b} ± 0.5	78.5^{ab} ± 1.2
JX				
	Tiny	69.7 ± 2.4	72.8 ± 0.8	72 ± 1.0
	Small	73.8 ± 2.0	78.1 ± 0.8	74.5 ± 1.2
	Average	72.6^{a} ± 1.8	79.1^{b} ± 0.8	75.8^{ab} ± 1.4
	Big	67.1^{a} ± 1.8	76.6^{b} ± 0.8	76.7^{b} ± 1.5
	Huge	72.5^{a} ± 1.6	78.4^{b} ± 0.7	73.9^{ab} ± 1.8
J				
	Tiny	55.8^{a} ± 5.0	67.9^{ab} ± 1.5	71.3^{b} ± 1.5
	Small	69.9 ± 3.4	74.5 ± 1.3	74.9 ± 1.6
	Average	62.7^{a} ± 3.4	74.8^{b} ± 1.2	74.5^{b} ± 1.8
	Big	69.9 ± 2.4	74.9 ± 1.2	75.8 ± 2.1
	Huge	67.1 ± 1.8	73.0 ± 1.2	75.7 ± 2.6

Values within a row with different superscripts differ at the 95% confidence interval.
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix IV. Table 7. Predicted stayability (STAY) ± SEM to calving as four-year-old provided they were reared of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

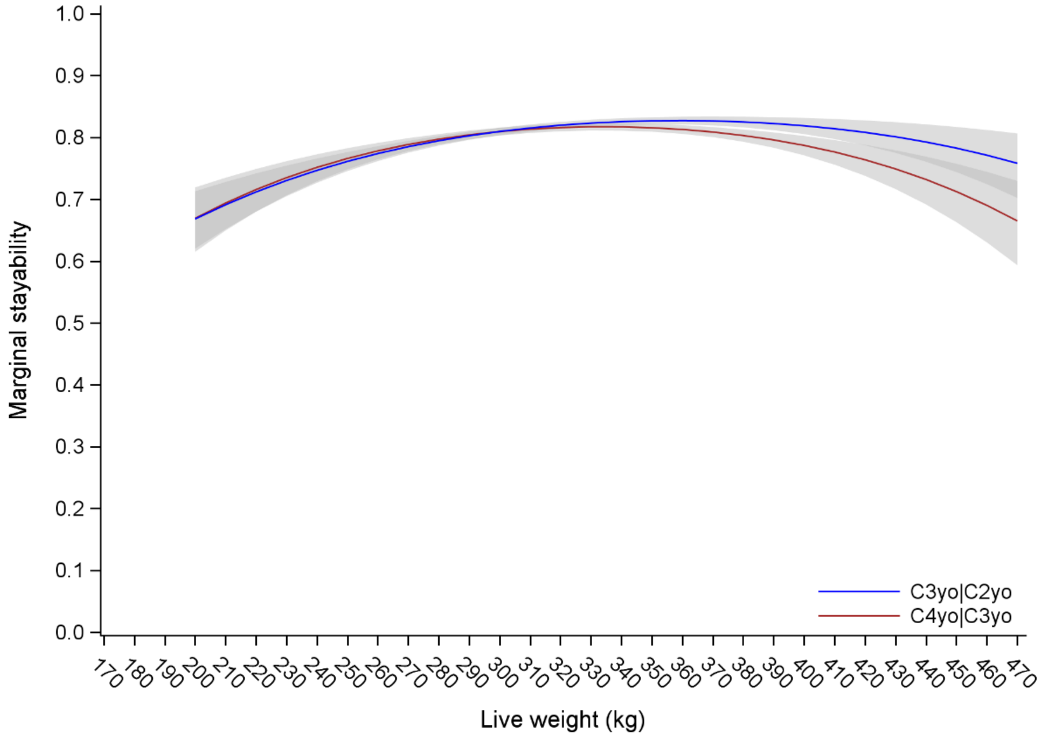
Breed group and LWT category		STAY(C4yo|rear)		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	$46.9^{a} \pm 1.6$	$55.2^{b} \pm 0.7$	$55.4^{b} \pm 0.9$
	Small	$47.7^{a} \pm 1.8$	$59.2^{b} \pm 0.7$	$60.8^{b} \pm 1.0$
	Average	$50.9^{a} \pm 2.0$	$60.0^{b} \pm 0.7$	$58.8^{b} \pm 1.0$
	Big	$51.4^{a} \pm 2.2$	$62.7^{b} \pm 0.7$	$62.7^{b} \pm 1.1$
	Huge	$57.3^{a} \pm 2.0$	$63.4^{b} \pm 0.7$	$59.0^{a} \pm 1.3$
FX				
	Tiny	$54.1^{a} \pm 1.4$	$59.8^{b} \pm 0.6$	$59.4^{b} \pm 0.8$
	Small	$54.5^{a} \pm 1.5$	$63.2^{b} \pm 0.6$	$61.2^{b} \pm 0.9$
	Average	$59.5^{a} \pm 1.5$	$63.5^{b} \pm 0.6$	$62.6^{ab} \pm 1.0$
	Big	$57.2^{a} \pm 1.7$	$63.8^{b} \pm 0.6$	$63.4^{b} \pm 1.0$
	Huge	$57.1^{a} \pm 1.8$	$65.5^{b} \pm 0.6$	$63.7^{b} \pm 1.1$
FJ				
	Tiny	$53.4^{a} \pm 1.8$	$60.3^{b} \pm 0.7$	$59.4^{b} \pm 0.9$
	Small	$58.9^{a} \pm 1.7$	$64.7^{b} \pm 0.7$	$62.9^{ab} \pm 1.1$
	Average	$55.5^{a} \pm 1.7$	$65.1^{b} \pm 0.7$	$63.9^{b} \pm 1.2$
	Big	$57.9^{a} \pm 1.7$	$65.4^{b} \pm 0.7$	$65.0^{b} \pm 1.3$
	Huge	$59.5^{a} \pm 1.7$	$66.5^{b} \pm 0.7$	$64.9^{ab} \pm 1.4$
JX				
	Tiny	54.1 ± 2.6	59.6 ± 0.9	58.5 ± 1.1
	Small	58.7 ± 2.3	63.3 ± 0.9	62.3 ± 1.4
	Average	$58.6^{a} \pm 2.0$	$65.4^{b} \pm 0.9$	$61.5^{ab} \pm 1.6$
	Big	$51.7^{a} \pm 2.0$	$64.6^{b} \pm 0.9$	$65.0^{b} \pm 1.7$
	Huge	$57.2^{a} \pm 1.9$	$63.6^{b} \pm 0.9$	$60^{ab} \pm 2.0$
J				
	Tiny	$42.6^{a} \pm 4.6$	$52.4^{ab} \pm 1.5$	$55.7^{b} \pm 1.6$
	Small	51.9 ± 3.5	58.6 ± 1.4	59.5 ± 1.8
	Average	53.8 ± 3.4	61.3 ± 1.4	61.6 ± 2.0
	Big	56.2 ± 2.5	60.6 ± 1.4	59.9 ± 2.4
	Huge	$51.7^{a} \pm 1.9$	$59.1^{b} \pm 1.4$	$59.9^{ab} \pm 3$

Values within a row with different superscripts differ at the 95% confidence interval. F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

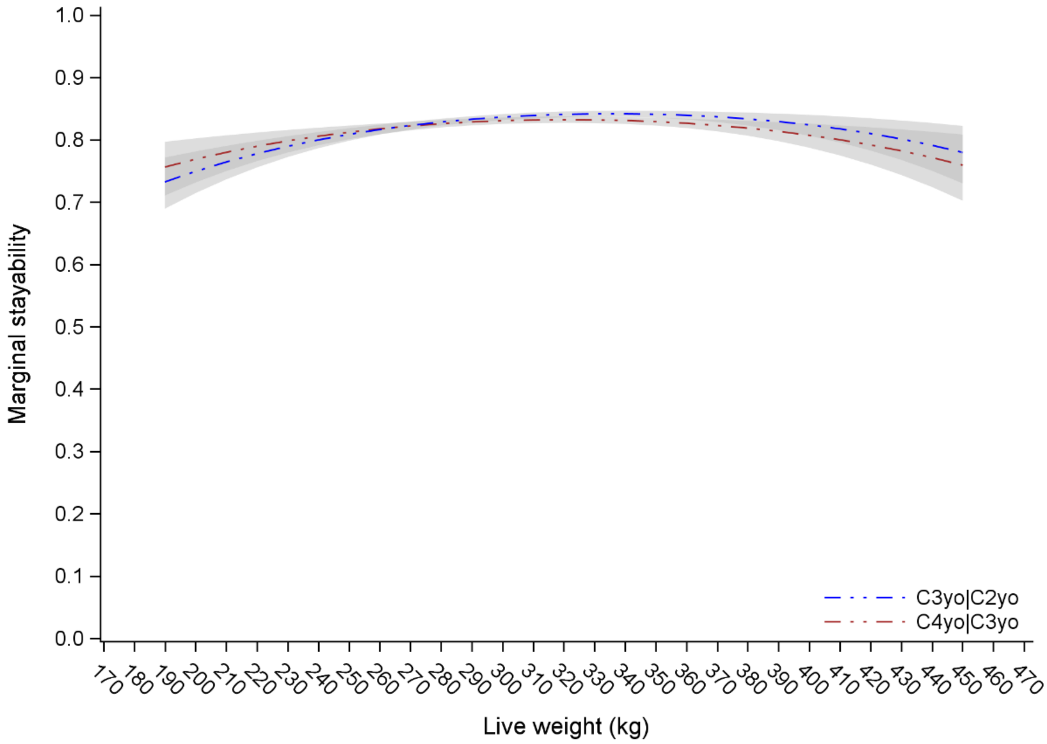
8.1.2 Marginal Stayability

Appendix IV. Table 8. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at six, 12 and 15 months of age on marginal stayability (MSTAY) from calving as a two-year-old to calving as a three-year-old; P(C3yo|C2yo), calving as a three-year-old to calving as a four-year-old; P(C4yo|C3yo) for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers.

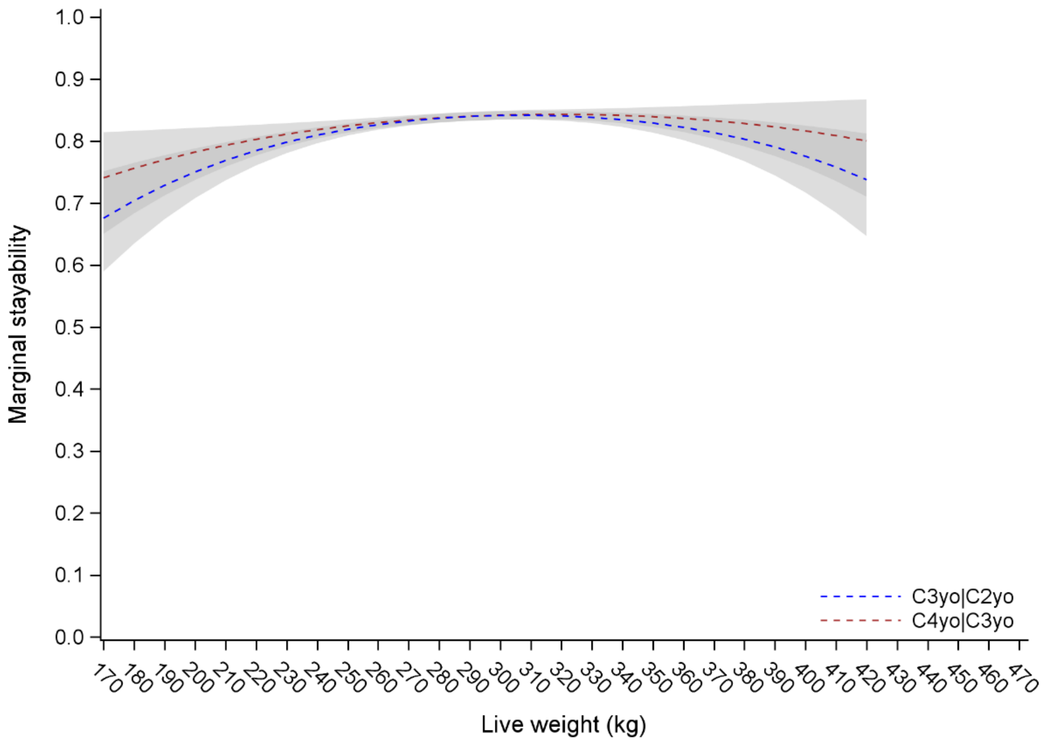
	Intercept	P value	Linear	P value	Quadratic	P value
			6 months of age			
P(C3yo|C2yo)						
F	-0.16 ± 0.43	0.709	0.016 ± 0.005	0.002	-0.00004 ± 0.00002	0.025
FX	0.25 ± 0.40	0.538	0.014 ± 0.005	0.006	-0.00003 ± 0.00002	0.038
FJ	-1.33 ± 0.48	0.005	0.035 ± 0.006	<0.001	-0.00010 ± 0.00002	<0.001
JX	-0.25 ± 0.62	0.685	0.024 ± 0.009	0.006	-0.00007 ± 0.00003	0.013
J	-0.92 ± 0.83	0.267	0.030 ± 0.012	0.014	-0.00009 ± 0.00004	0.047
P(C4yo|C3yo)						
F	-0.63 ± 0.47	0.183	0.024 ± 0.006	<0.001	-0.00007 ± 0.00002	<0.001
FX	0.50 ± 0.44	0.259	0.012 ± 0.006	0.037	-0.00003 ± 0.00002	0.085
FJ	-0.36 ± 0.53	0.499	0.025 ± 0.007	<0.001	-0.00008 ± 0.00002	0.001
JX	0.49 ± 0.70	0.483	0.014 ± 0.010	0.146	-0.00004 ± 0.00003	0.212
J	0.13 ± 0.93	0.886	0.017 ± 0.014	0.215	-0.00005 ± 0.00005	0.330
			12 months of age			
P(C3yo|C2yo)						
F	-1.74 ± 0.56	0.002	0.022 ± 0.004	<0.001	-0.00004 ± 0.00001	<0.001
FX	-0.36 ± 0.54	0.503	0.014 ± 0.004	0.001	-0.00002 ± 0.00001	0.006
FJ	-1.34 ± 0.67	0.045	0.021 ± 0.006	<0.001	-0.00003 ± 0.00001	0.004
JX	-2.32 ± 0.87	0.008	0.032 ± 0.008	<0.001	-0.00007 ± 0.00002	<0.001
J	-3.26 ± 1.27	0.010	0.039 ± 0.012	0.001	-0.00008 ± 0.00003	0.005
P(C4yo|C3yo)						
F	-2.66 ± 0.62	<0.001	0.031 ± 0.005	<0.001	-0.00006 ± 0.00001	<0.001
FX	-0.35 ± 0.59	0.552	0.014 ± 0.005	0.003	-0.00003 ± 0.00001	0.007
FJ	-0.18 ± 0.75	0.806	0.015 ± 0.006	0.020	-0.00003 ± 0.00001	0.030
JX	-0.83 ± 1.00	0.407	0.020 ± 0.009	0.024	-0.00004 ± 0.00002	0.043
J	-1.98 ± 1.44	0.170	0.030 ± 0.013	0.023	-0.00006 ± 0.00003	0.035
			15 months of age			
P(C3yo|C2yo)						
F	-2.85 ± 0.70	<0.001	0.025 ± 0.004	<0.001	-0.00003 ± 0.00001	<0.001
FX	-1.85 ± 0.69	0.007	0.021 ± 0.004	<0.001	-0.00003 ± 0.00001	<0.001
FJ	-2.59 ± 0.85	0.002	0.025 ± 0.006	<0.001	-0.00004 ± 0.00001	<0.001
JX	-3.04 ± 1.09	0.005	0.031 ± 0.008	<0.001	-0.00005 ± 0.00001	<0.001
J	-4.31 ± 1.54	0.005	0.039 ± 0.012	0.001	-0.00006 ± 0.00002	0.003
P(C4yo|C3yo)						
F	-3.42 ± 0.78	<0.001	0.029 ± 0.005	<0.001	-0.00004 ± 0.00001	<0.001
FX	-1.21 ± 0.76	0.111	0.018 ± 0.005	<0.001	-0.00003 ± 0.00001	<0.001
FJ	-0.64 ± 0.97	0.507	0.015 ± 0.006	0.020	-0.00002 ± 0.00001	0.025
JX	-1.23 ± 1.25	0.328	0.018 ± 0.009	0.034	-0.00003 ± 0.00002	0.053
J	-3.27 ± 1.76	0.064	0.034 ± 0.013	0.009	-0.00006 ± 0.00002	0.013



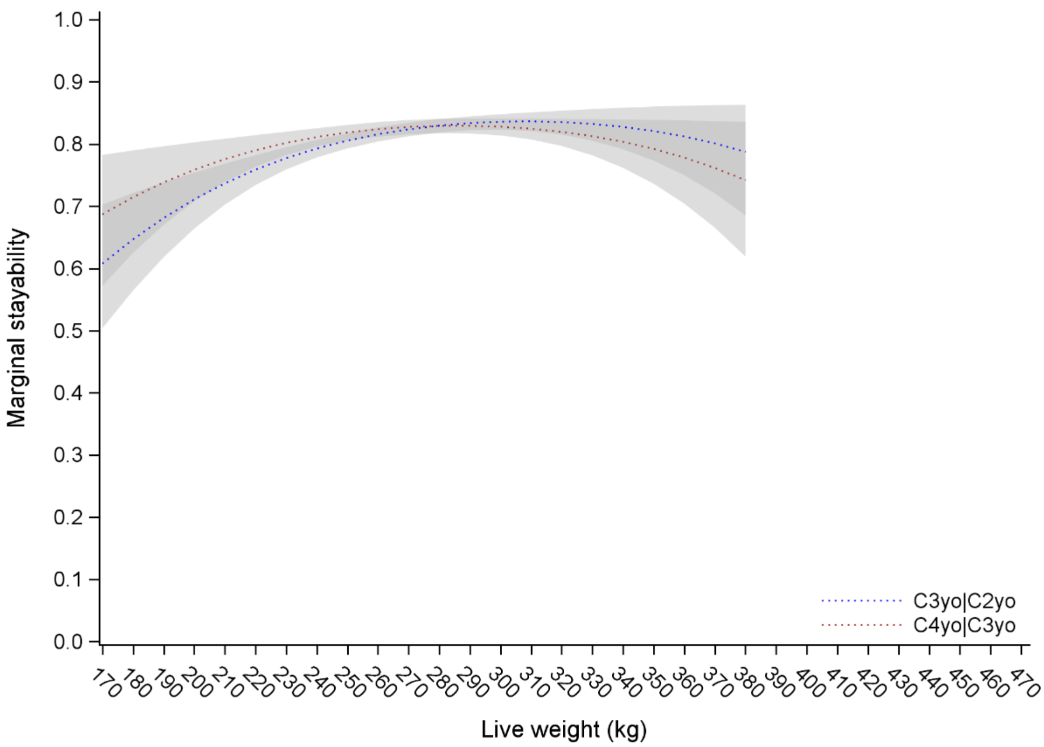
Appendix IV. Figure 9. Relationship between live weight (LWT) at 15 months of age and marginal stayability of Holstein-Friesian (F) heifers that calved as three-year-olds (C3yo) provided they calved as two-year-olds (C3yo|C2yo) and heifers that calved as four-year-olds (C4yo) provided they calved as three-year-olds (C4yo|C3yo). Shaded area indicates 95% confidence intervals.



Appendix IV. Figure 10. Relationship between live weight (LWT) at 15 months of age and marginal stayability of Holstein-Friesian crossbred (FX) heifers that calved as three-year-olds (C3yo) provided they calved as two-year-olds (C3yo|C2yo) and heifers that calved as four-year-olds (C4yo) provided they calved as three-year-olds (C4yo|C3yo). Shaded area indicates 95% confidence intervals.



Appendix IV. Figure 11. Relationship between live weight (LWT) at 15 months of age and marginal stayability of Jersey crossbred (JX) heifers that calved as three-year-olds (C3yo) provided they calved as two-year-olds (C3yo|C2yo) and heifers that calved as four-year-olds (C4yo) provided they calved as three-year-olds (C4yo|C3yo). Shaded area indicates 95% confidence intervals.



Appendix IV. Figure 12. Relationship between live weight (LWT) at 15 months of age and marginal stayability of Jersey crossbred (JX) heifers that calved as three-year-olds (C3yo) provided they calved as two-year-olds (C3yo|C2yo) and heifers that calved as four-year-olds (C4yo) provided they calved as three-year-olds (C4yo|C3yo). Shaded area indicates 95% confidence intervals.

Appendix IV. Table 9. Least-squares means ± SEM of marginal stayability to calving as a three-year-old (C3yo) provided they calved as a two-year-old (C2yo) and calved as a four-year-old (C4yo) provided they C3yo for heifers that were tiny, small, average, big or huge within breed group at 21 months of age.

Breed and LWT rank	P(C3yo|C2yo)	P(C4yo|C3yo)
F		
Tiny	$78.7^{a} \pm 0.5$	$78.4^{a} \pm 0.6$
Small	$80.6^{b} \pm 0.5$	$80.5^{b} \pm 0.5$
Average	$81.7^{bc} \pm 0.5$	$79.1^{a} \pm 0.5$
Big	$82.1^{c} \pm 0.4$	$80.7^{b} \pm 0.5$
Huge	$81.3^{b} \pm 0.5$	$78.7^{a} \pm 0.6$
FX		
Tiny	$81.1^{a} \pm 0.4$	$81.7^{b} \pm 0.4$
Small	$83.3^{b} \pm 0.4$	$81.9^{ab} \pm 0.4$
Average	$83.4^{b} \pm 0.4$	$82.4^{ab} \pm 0.4$
Big	$83.5^{b} \pm 0.4$	$81.5^{b} \pm 0.4$
Huge	$83.6^{b} \pm 0.4$	$80.7^{a} \pm 0.4$
FJ		
Tiny	$81.2^{a} \pm 0.5$	$82.1^{a} \pm 0.5$
Small	$83.6^{b} \pm 0.5$	$83.7^{b} \pm 0.5$
Average	$84.4^{b} \pm 0.4$	$83.4^{ab} \pm 0.5$
Big	$84.6^{b} \pm 0.4$	$83.2^{ab} \pm 0.5$
Huge	$84.6^{b} \pm 0.4$	$82.3^{a} \pm 0.5$
JX		
Tiny	$80.8^{a} \pm 0.7$	$82.0^{a} \pm 0.7$
Small	$83.5^{bc} \pm 0.6$	$82.4^{a} \pm 0.7$
Average	$84.5^{c} \pm 0.6$	$82.8^{ab} \pm 0.6$
Big	$82.9^{b} \pm 0.6$	$84.3^{b} \pm 0.6$
Huge	$82.5^{ab} \pm 0.6$	$81.6^{a} \pm 0.7$
J		
Tiny	$76.8^{a} \pm 1.1$	$78.8^{a} \pm 1.2$
Small	$81.9^{bc} \pm 0.9$	$79.9^{a} \pm 1.0$
Average	$80.4^{b} \pm 0.9$	$83.5^{b} \pm 1.0$
Big	$83.0^{c} \pm 0.9$	$81.5^{ab} \pm 1.0$
Huge	$82.3^{bc} \pm 0.9$	$80.5^{a} \pm 1.1$

$^{a-d}$Values within column and breed group with different superscripts differ between LWT categories ($P<0.05$).
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix IV. Table 10. Predicted marginal stayability (MSTAY) ± SEM to calving as three-year-old provided they calved as a two-year-old of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21)

Breed group and LWT category		MSTAY(C3yo|C2yo)		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	75.0^{a} ± 1.5	78.7^{b} ± 0.5	79.7^{b} ± 0.7
	Small	74.6^{a} ± 1.7	80.2^{b} ± 0.6	83.1^{c} ± 0.8
	Average	78.8 ± 1.7	81.6 ± 0.5	82.6 ± 0.8
	Big	75.5^{a} ± 1.9	81.9^{b} ± 0.5	83.7^{b} ± 0.8
	Huge	79.9 ± 1.6	81.4 ± 0.6	81.7 ± 1.0
FX				
	Tiny	81.0 ± 1.1	81.2 ± 0.5	80.5 ± 0.6
	Small	80.4 ± 1.3	83.5 ± 0.4	83.1 ± 0.7
	Average	83.1 ± 1.2	83.1 ± 0.5	84.1 ± 0.8
	Big	81.6 ± 1.3	83.4 ± 0.5	84.0 ± 0.8
	Huge	81.7 ± 1.3	83.8 ± 0.4	83.3 ± 0.9
FJ				
	Tiny	77.3^{a} ± 1.6	80.9^{ab} ± 0.6	82.5^{b} ± 0.7
	Small	81.7 ± 1.3	83.2 ± 0.6	84.7 ± 0.8
	Average	79.5^{a} ± 1.4	84.4^{b} ± 0.5	85.7^{b} ± 0.9
	Big	81.5^{a} ± 1.4	84.3^{ab} ± 0.5	86.6^{b} ± 1.0
	Huge	81.7 ± 1.3	84.8 ± 0.5	85.2 ± 1.1
JX				
	Tiny	80.2 ± 2.2	80.9 ± 0.8	80.8 ± 0.9
	Small	82.6 ± 1.7	83.9 ± 0.7	82.6 ± 1.1
	Average	80.8 ± 1.6	85.0 ± 0.7	84.4 ± 1.2
	Big	76.6^{a} ± 1.7	83.2^{b} ± 0.7	85.2^{b} ± 1.3
	Huge	80.2 ± 1.5	83.1 ± 0.7	80.9 ± 1.7
J				
	Tiny	65.1^{a} ± 5.0	75.2^{ab} ± 1.4	79.3^{b} ± 1.3
	Small	77.5 ± 3.1	81.2 ± 1.2	83.8 ± 1.4
	Average	72.6^{a} ± 3.1	81.4^{b} ± 1.1	80.4^{ab} ± 1.6
	Big	81.4 ± 2.0	83.4 ± 1.1	82.4 ± 1.9
	Huge	79.3 ± 1.6	82.6 ± 1.1	85.4 ± 2.2

Values within a row with different superscripts differ at the 95% confidence interval.
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix IV. Table 11. Predicted marginal stayability (MSTAY) ± SEM to calving as four-year-old provided they calved as a three-year-old of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21)

Breed group and LWT category		MSTAY(C4yo|C3yo)		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	72.9[a] ± 1.7	78.1[b] ± 0.6	80.0[b] ± 0.8
	Small	75.8[a] ± 1.9	80.1[ab] ± 0.6	82.0[b] ± 0.9
	Average	73.8[a] ± 2.1	79.2[b] ± 0.6	79.7[b] ± 0.9
	Big	75.0[a] ± 2.2	80.6[b] ± 0.6	81.8[b] ± 0.9
	Huge	75.1 ± 1.9	79.4 ± 0.6	77.7 ± 1.2
FX				
	Tiny	78.7[a] ± 1.4	81.1[ab] ± 0.5	83.0[b] ± 0.6
	Small	79.4 ± 1.4	81.7 ± 0.5	82.8 ± 0.8
	Average	80.4 ± 1.4	82.1 ± 0.5	83.4 ± 0.8
	Big	78.1[a] ± 1.6	81.1[ab] ± 0.5	83.4[b] ± 0.9
	Huge	75.7[a] ± 1.7	80.7[b] ± 0.5	82.0[b] ± 1.0
FJ				
	Tiny	80.7 ± 1.7	82.5 ± 0.6	81.8 ± 0.8
	Small	81.1 ± 1.5	84.3 ± 0.6	83.0 ± 0.9
	Average	80.2 ± 1.6	83.6 ± 0.6	83.5 ± 1.0
	Big	80.5 ± 1.6	83.0 ± 0.6	84.7 ± 1.1
	Huge	80.4 ± 1.6	82.0 ± 0.6	83.6 ± 1.2
JX				
	Tiny	79.1 ± 2.4	82.3 ± 0.8	82.2 ± 1.0
	Small	80.4 ± 2.1	81.6 ± 0.8	84.6 ± 1.2
	Average	81.5 ± 1.8	83.3 ± 0.8	81.8 ± 1.4
	Big	78.0[a] ± 1.9	84.7[b] ± 0.7	85.7[b] ± 1.4
	Huge	80.1 ± 1.8	81.6 ± 0.8	82.2 ± 1.8
J				
	Tiny	76.8 ± 4.9	78.4 ± 1.5	79.3 ± 1.5
	Small	76.0 ± 3.4	79.9 ± 1.3	80.6 ± 1.6
	Average	86.8 ± 2.8	82.8 ± 1.2	84.4 ± 1.8
	Big	81.4 ± 2.2	81.9 ± 1.2	80.4 ± 2.2
	Huge	77.6 ± 1.8	81.7 ± 1.2	80.9 ± 2.6

Values within a row with different superscripts differ at the 95% confidence interval.
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix V

Appendix V includes the tables of regression coefficients for the linear and quadratic effects of LWT at six, 12 and 15 months of age on calving rate and re-calving rate for all five breed groups studied in Chapter 6. Additionally, figures illustrating the relationships between LWT at 15 months of age and calving rate and re-calving rate for F, FX, JX and J heifers are also included.

Appendix V also includes tables comparing heifers that were 45, 55 or 65% of their 21-month LWT at 12 months of age for calving rate and re-calving rate for all five breed groups and five LWT categories studied in Chapter 6.

8.1.3 Calving Rate

Appendix V. Table 1. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at six months of age (6m) on calving rate within 21 days of planned start of calving (C21) for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers that calved as two-year-old (C21_2yo), three-year-old (C21_3yo) or four-year-olds (C21_4yo)

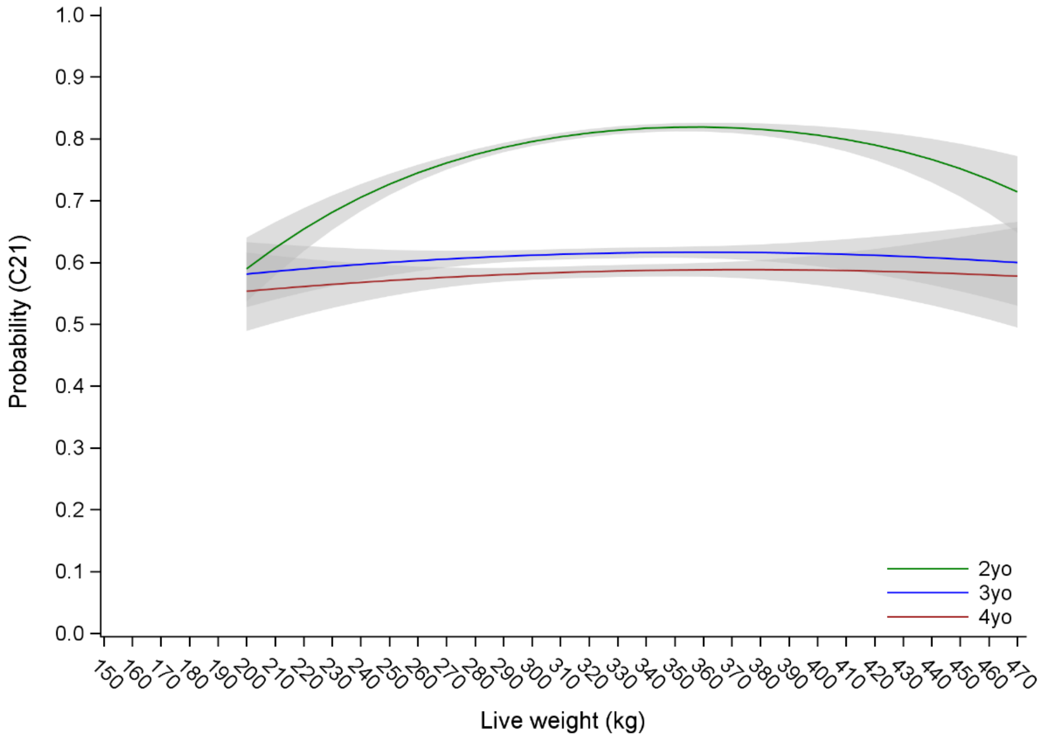
	Intercept	P-value	Linear	P-value	Quadratic	P-value
C21_2yo						
F	-0.64 ± 0.45	0.156	0.022 ± 0.006	<0.001	-0.00006 ± 0.00002	0.001
FX	-0.87 ± 0.40	0.030	0.028 ± 0.005	<0.001	-0.00008 ± 0.00002	<0.001
FJ	-0.90 ± 0.48	0.061	0.030 ± 0.006	<0.001	-0.00009 ± 0.00002	<0.001
JX	0.04 ± 0.63	0.943	0.018 ± 0.009	0.033	-0.00006 ± 0.00003	0.049
J	1.27 ± 0.88	0.148	<0.001± 0.013	0.982	0.00001 ± 0.00005	0.886
C21_3yo						
F	-0.61 ± 0.43	0.161	0.013 ± 0.005	0.016	-0.00004 ± 0.00002	0.022
FX	0.25 ± 0.38	0.510	0.004 ± 0.005	0.463	-0.00001 ± 0.00002	0.510
FJ	-0.36 ± 0.47	0.446	0.013 ± 0.006	0.039	-0.00004 ± 0.00002	0.040
JX	-0.35 ± 0.59	0.549	0.011 ± 0.008	0.177	-0.00003 ± 0.00003	0.265
J	0.13 ± 0.82	0.876	0.005 ± 0.012	0.673	-0.00001 ± 0.00004	0.762
C21_4yo						
F	-0.30 ± 0.50	0.557	0.008 ± 0.006	0.212	-0.00002 ± 0.00002	0.224
FX	0.42 ± 0.45	0.341	-0.001 ± 0.006	0.892	0.00000 ± 0.00002	0.796
FJ	-0.53 ± 0.54	0.323	0.013 ± 0.007	0.067	-0.00004 ± 0.00002	0.081
JX	-1.22 ± 0.67	0.067	0.023 ± 0.009	0.012	-0.00007 ± 0.00003	0.015
J	-0.64 ± 0.92	0.487	0.018 ± 0.013	0.179	-0.00007 ± 0.00005	0.136

Appendix V. Table 2. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at 12 months of age (12m) on calving rate within 21 days of planned start of calving (CR21) for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers that calved as two-year-old (C21_2yo), three-year-old (C21_3yo) or four-year-old (C21_4yo)

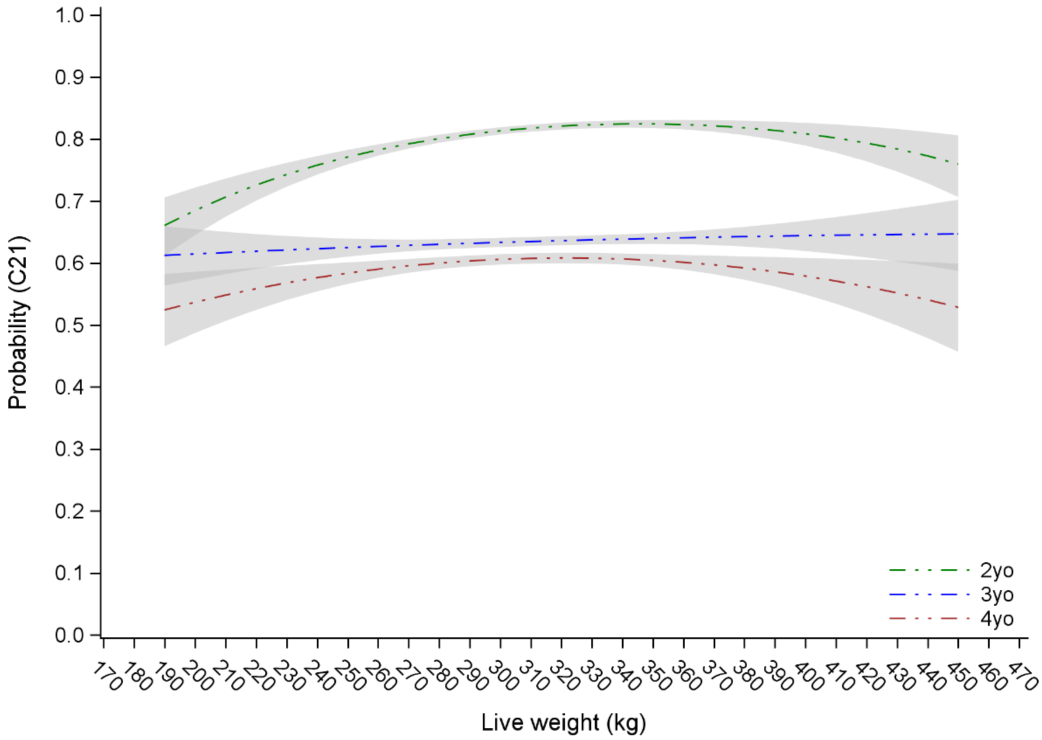
	Intercept	P-value	Linear	P-value	Quadratic	P-value
C21_2yo						
F	-3.23 ± 0.58	<0.001	0.035 ± 0.005	<0.001	-0.00006 ± 0.00001	<0.001
FX	-2.60 ± 0.53	<0.001	0.032 ± 0.004	<0.001	-0.00006 ± 0.00001	<0.001
FJ	-3.00 ± 0.65	<0.001	0.037 ± 0.006	<0.001	-0.00008 ± 0.00001	<0.001
JX	-1.62 ± 0.89	0.067	0.027 ± 0.008	<0.001	-0.00006 ± 0.00002	<0.001
J	-1.34 ± 1.34	0.317	0.027 ± 0.012	0.027	-0.00007 ± 0.00003	0.017
C21_3yo						
F	-0.16 ± 0.57	0.777	0.004 ± 0.004	0.367	-0.00001 ± 0.00001	0.487
FX	0.06 ± 0.51	0.900	0.003 ± 0.004	0.483	0.00000 ± 0.00001	0.675
FJ	-1.48 ± 0.63	0.020	0.017 ± 0.005	0.002	-0.00003 ± 0.00001	0.004
JX	-0.78 ± 0.86	0.359	0.010 ± 0.007	0.198	-0.00002 ± 0.00002	0.328
J	1.61 ± 1.31	0.219	-0.010 ± 0.012	0.420	0.00002 ± 0.00003	0.420
C21_4yo						
F	-0.48 ± 0.68	0.478	0.005 ± 0.005	0.312	-0.00001 ± 0.00001	0.423
FX	-0.97 ± 0.59	0.099	0.011 ± 0.005	0.028	-0.00002 ± 0.00001	0.045
FJ	-1.39 ± 0.73	0.057	0.015 ± 0.006	0.013	-0.00003 ± 0.00001	0.017
JX	-2.83 ± 0.96	0.003	0.028 ± 0.008	0.001	-0.00006 ± 0.00002	0.001
J	-2.11 ± 1.54	0.170	0.026 ± 0.014	0.065	-0.00007 ± 0.00003	0.043

Appendix V. Table 3. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at 15 months of age on calving rate within 21 days of planned start of calving (CR21) for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers that calved as two-year-old (C21_2yo), three-year-old (C21_3yo) or four-year-old (C21_4yo)

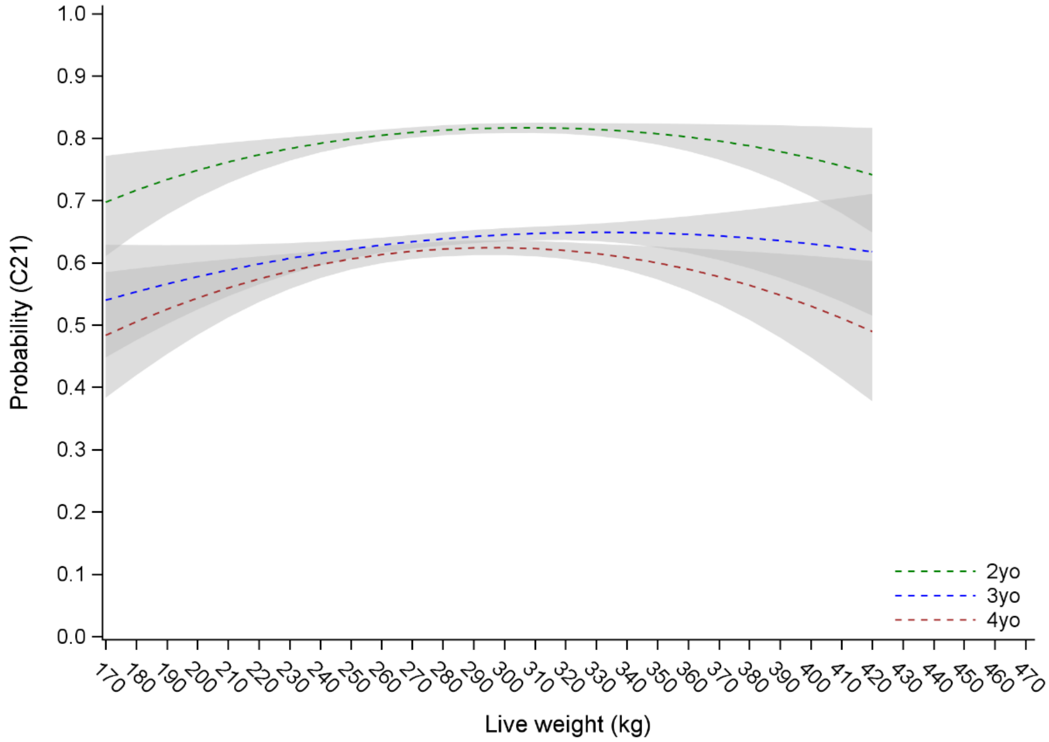
	Intercept	P-value	Linear	P-value	Quadratic	P-value
C21_2yo						
F	-4.41 ± 0.73	<0.001	0.033 ± 0.005	<0.001	-0.00005 ± 0.00001	<0.001
FX	-2.79 ± 0.69	<0.001	0.025 ± 0.004	<0.001	-0.00004 ± 0.00001	<0.001
FJ	-4.03 ± 0.84	<0.001	0.035 ± 0.006	<0.001	-0.00005 ± 0.00001	<0.001
JX	-1.80 ± 1.12	0.107	0.022 ± 0.008	0.005	-0.00003 ± 0.00001	0.008
J	-1.04 ± 1.70	0.541	0.018 ± 0.012	0.151	-0.00003 ± 0.00002	0.147
C21_3yo						
F	-0.27 ± 0.72	0.713	0.004 ± 0.004	0.350	-0.00001 ± 0.00001	0.396
FX	0.22 ± 0.66	0.738	0.002 ± 0.004	0.706	0.00000 ± 0.00001	0.812
FJ	-2.24 ± 0.81	0.006	0.018 ± 0.005	0.001	-0.00003 ± 0.00001	0.001
JX	-1.29 ± 1.08	0.229	0.012 ± 0.007	0.119	-0.00002 ± 0.00001	0.171
J	2.27 ± 1.65	0.169	-0.012 ± 0.012	0.322	0.00002 ± 0.00002	0.348
C21_4yo						
F	-0.30 ± 0.86	0.726	0.004 ± 0.005	0.504	0.00000 ± 0.00001	0.559
FX	-1.60 ± 0.76	0.035	0.013 ± 0.005	0.009	-0.00002 ± 0.00001	0.011
FJ	-1.20 ± 0.93	0.196	0.011 ± 0.006	0.078	-0.00002 ± 0.00001	0.091
JX	-2.65 ± 1.19	0.026	0.021 ± 0.008	0.009	-0.00004 ± 0.00001	0.010
J	-2.45 ± 1.88	0.193	0.024 ± 0.014	0.088	-0.00005 ± 0.00003	0.062



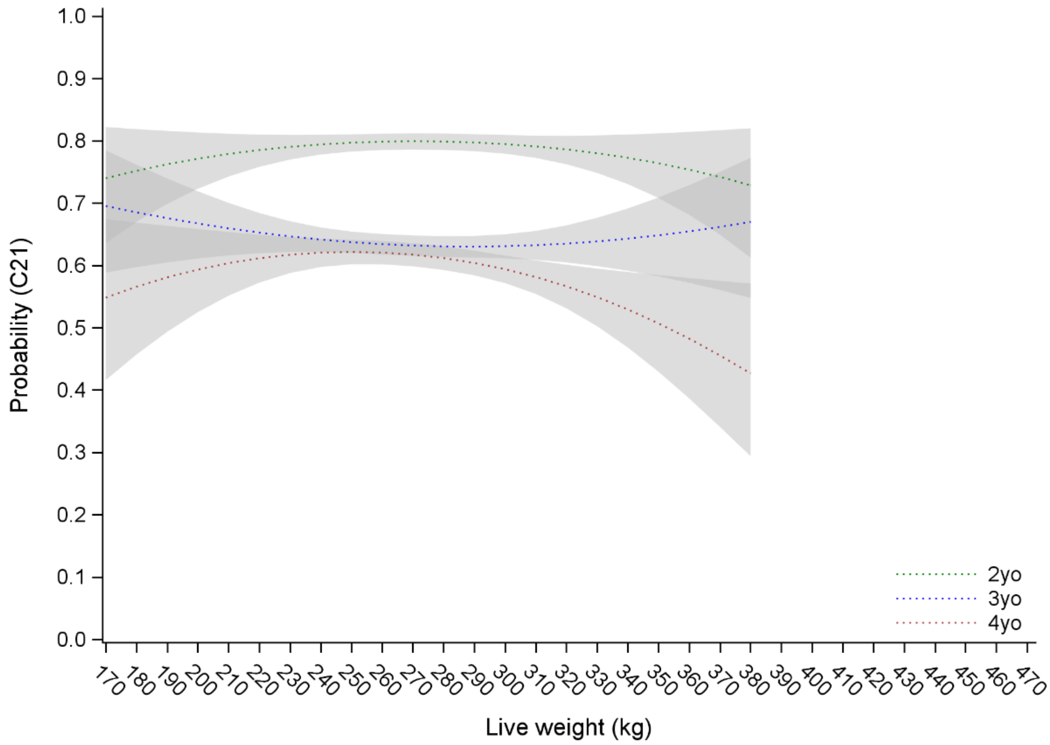
Appendix V. Figure 1. Relationship between live weight (LWT) at 15 months of age and calving rate within 21 days planned start of calving (C21) for Holstein-Friesian (F) heifers that calved that year as two- (2yo), three- (3yo) or four-year-olds (4yo).



Appendix V. Figure 2. Relationship between live weight (LWT) at 15 months of age and calving rate within 21 days planned start of calving (C21) for Holstein-Friesian crossbred (FX) heifers that calved that year as two- (2yo), three- (3yo) or four-year-olds (4yo).



Appendix V. Figure 3. Relationship between live weight (LWT) at 15 months of age and calving rate within 21 days planned start of calving (C21) for Jersey crossbred (JX) heifers that calved that year as two- (2yo), three- (3yo) or four-year-olds (4yo).

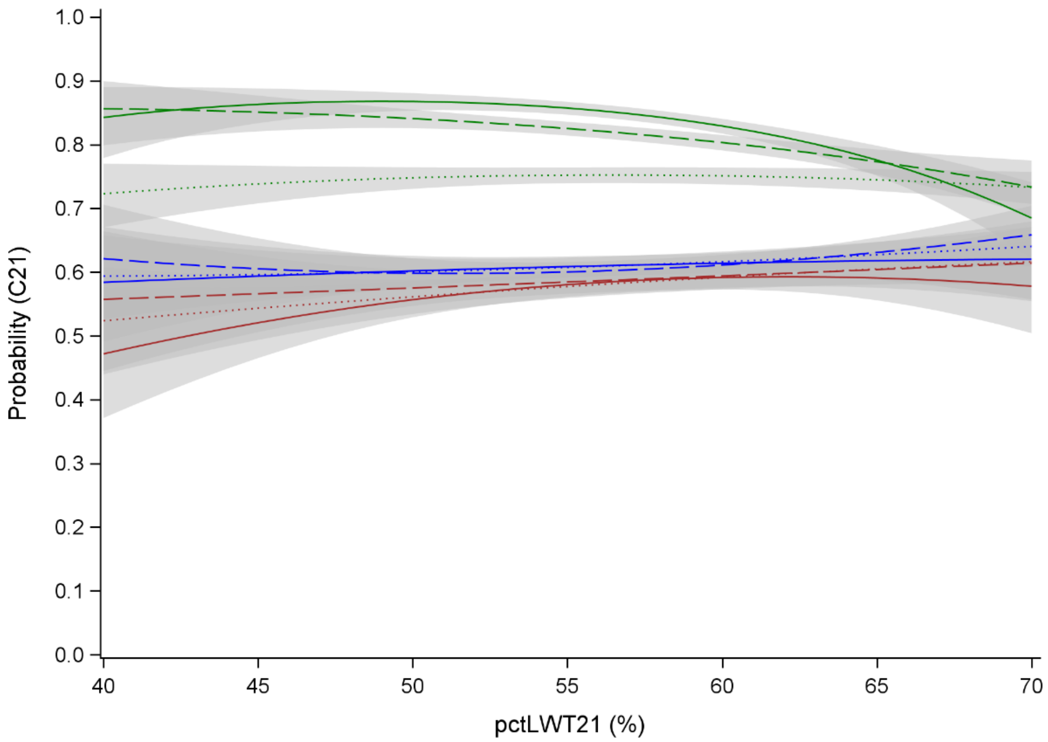


Appendix V. Figure 4. Relationship between live weight (LWT) at 15 months of age and calving rate within 21 days planned start of calving (C21) for Jersey (J) heifers that calved that year as two- (2yo), three- (3yo) or four-year-olds (4yo).

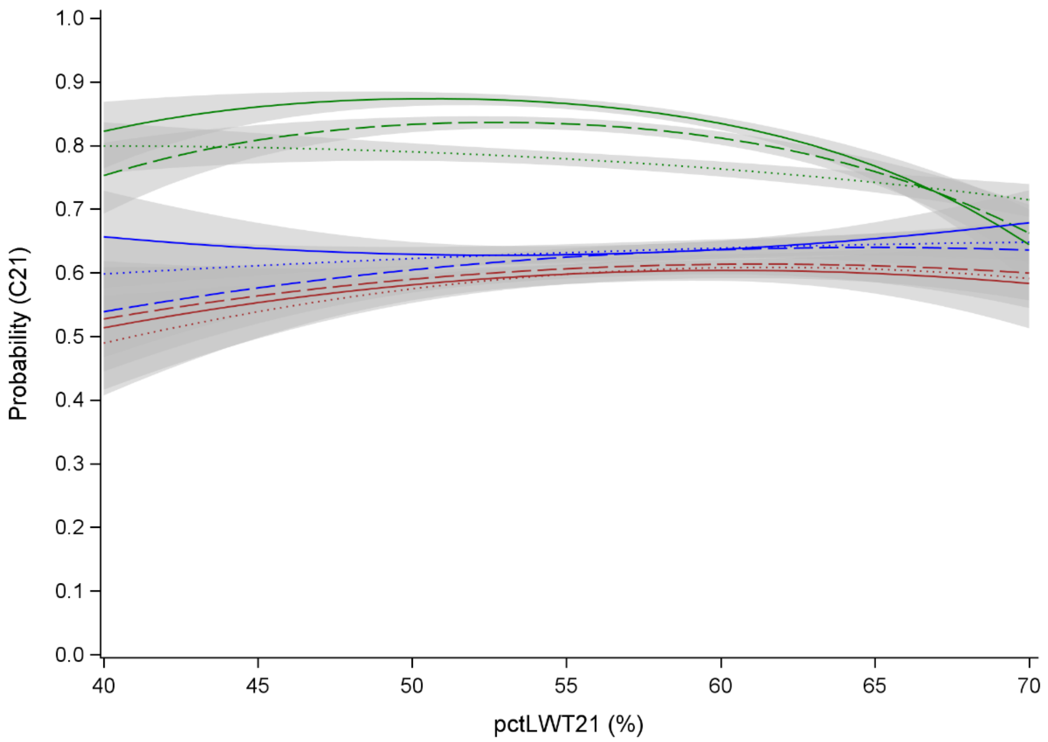
Appendix V. Table 4. Least-squares means ± SEM of 21-day calving rate (C21) of Holstein-Friesian (F), Holstein-Friesian-crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ) Jersey crossbred (JX) and Jersey (J) heifers that were tiny, small, average, big or huge at 21 months of age.

Breed and LWT rank		C21_2yo	C21_3yo	C21_4yo
F				
	Tiny	$74.7^{a} \pm 0.6$	60.6 ± 0.7	56.8 ± 0.8
	Small	$79.1^{b} \pm 0.5$	59.3 ± 0.7	55.9 ± 0.8
	Average	$81.5^{c} \pm 0.5$	60.0 ± 0.7	57.2 ± 0.8
	Big	$82.3^{c} \pm 0.5$	60.7 ± 0.7	56.9 ± 0.8
	Huge	$84.2^{d} \pm 0.5$	60.0 ± 0.7	56.2 ± 0.8
FX				
	Tiny	$76.8^{a} \pm 0.5$	62.6 ± 0.6	57.8 ± 0.7
	Small	$80.0^{b} \pm 0.5$	62.7 ± 0.6	58.9 ± 0.7
	Average	$81.5^{c} \pm 0.4$	61.6 ± 0.6	58.8 ± 0.7
	Big	$83.1^{d} \pm 0.4$	62.3 ± 0.6	59.1 ± 0.7
	Huge	$84.7^{e} \pm 0.4$	62.5 ± 0.6	57.9 ± 0.7
FJ				
	Tiny	$76.4^{a} \pm 0.6$	63.4 ± 0.7	59.2 ± 0.8
	Small	$80.4^{b} \pm 0.5$	63.6 ± 0.7	60.4 ± 0.8
	Average	$81.0^{b} \pm 0.5$	62.8 ± 0.7	60.8 ± 0.8
	Big	$83.1^{c} \pm 0.5$	63.9 ± 0.7	60.0 ± 0.8
	Huge	$84.2^{c} \pm 0.5$	62.9 ± 0.7	60.3 ± 0.8
JX				
	Tiny	$77.4^{a} \pm 0.8$	$61.3^{a} \pm 0.9$	$58.8^{ab} \pm 1.1$
	Small	$79.4^{b} \pm 0.7$	$64.4^{b} \pm 0.9$	$61.2^{b} \pm 1.0$
	Average	$81.5^{c} \pm 0.7$	$62.9^{ab} \pm 0.9$	$61.6^{b} \pm 1.0$
	Big	$82.5^{cd} \pm 0.6$	$62.6^{ab} \pm 0.9$	$60.3^{b} \pm 1.0$
	Huge	$83.7^{d} \pm 0.6$	$62.6^{ab} \pm 0.9$	$57.4^{a} \pm 1.1$
J				
	Tiny	$75.0^{a} \pm 1.2$	$64.7^{b} \pm 1.4$	61.9 ± 1.6
	Small	$76.5^{a} \pm 1.1$	$62.3^{ab} \pm 1.3$	58.0 ± 1.5
	Average	$80.2^{b} \pm 1.0$	$62.8^{ab} \pm 1.3$	58.8 ± 1.5
	Big	$82.7^{c} \pm 0.9$	$60.1^{a} \pm 1.3$	58.5 ± 1.5
	Huge	$81.0^{bc} \pm 1.0$	$62.8^{ab} \pm 1.4$	58.4 ± 1.6

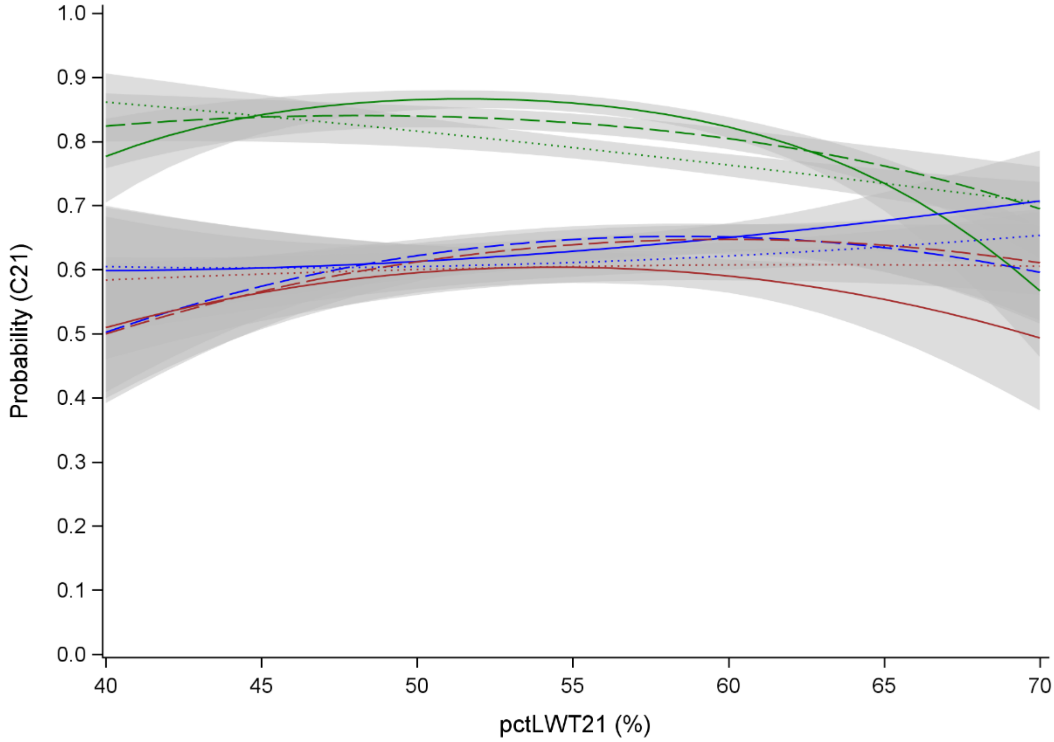
$^{a-d}$Values within column and breed group with different superscripts differ between LWT categories (P<0.05). Where C2yo is first calving as a two-year-old, C3yo is second calving as a three-year-old, and C4yo is third calving as a four-year-old.



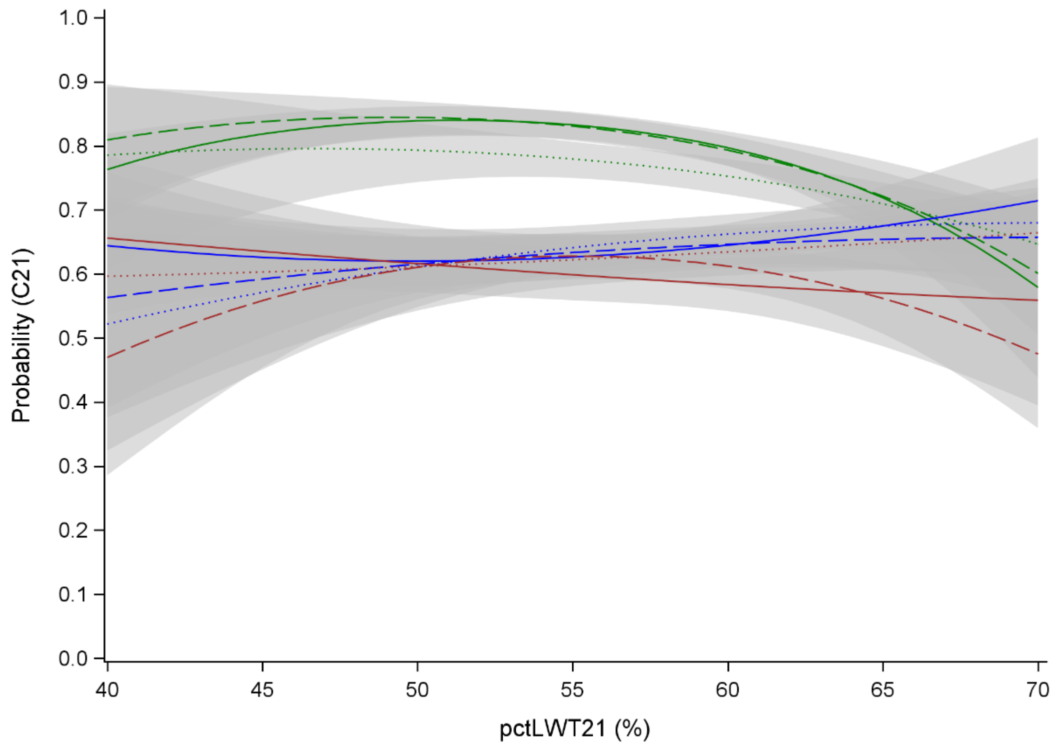
Appendix V. Figure 5. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of calving within 21 days of planned start of calving (C21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Holstein-Friesian (F) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.



Appendix V. Figure 6. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of calving within 21 days of planned start of calving (C21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Holstein-Friesian crossbred (FX) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.



Appendix V. Figure 7. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of calving within 21 days of planned start of calving (C21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Jersey crossbred (JX) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.



Appendix V. Figure 8. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of calving within 21 days of planned start of calving (C21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Jersey (J) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.

Appendix V. Table 5. Predicted 21-day calving rate ± SEM to calving as two-year-old (C21_2yo) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		C21_2yo		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	73.8 ± 1.5	75.2 ± 0.6	74.5 ± 0.9
	Small	81.7^{b} ± 1.5	80.7^{b} ± 0.6	74.2^{a} ± 1.0
	Average	85.1^{b} ± 1.4	82.5^{b} ± 0.5	77.3^{a} ± 1.0
	Big	86.5^{b} ± 1.4	83.8^{b} ± 0.5	76.5^{a} ± 1.0
	Huge	86.3^{b} ± 1.4	85.7^{b} ± 0.5	77.6^{a} ± 1.2
FX				
	Tiny	79.7^{b} ± 1.2	77.9^{b} ± 0.5	74.2^{a} ± 0.8
	Small	82.4^{b} ± 1.2	81.5^{b} ± 0.5	75.1^{a} ± 0.9
	Average	80.8^{b} ± 1.3	83.4^{b} ± 0.5	75.9^{a} ± 1.0
	Big	82.9^{a} ± 1.3	84.6^{a} ± 0.5	77.8^{b} ± 1.0
	Huge	86.1^{b} ± 1.2	86.6^{b} ± 0.4	76.8^{a} ± 1.1
FJ				
	Tiny	79.9^{b} ± 1.5	78.2^{b} ± 0.7	72.5^{a} ± 0.9
	Small	82.4^{b} ± 1.3	82.2^{b} ± 0.6	75.0^{a} ± 1.1
	Average	80.2^{ab} ± 1.4	82.8^{b} ± 0.6	75.8^{a} ± 1.2
	Big	83.2^{b} ± 1.3	85.0^{b} ± 0.5	76.0^{a} ± 1.4
	Huge	87.6^{b} ± 1.2	85.7^{b} ± 0.5	76.8^{a} ± 1.4
JX				
	Tiny	84.0^{b} ± 1.9	79.0^{b} ± 0.8	73.4^{a} ± 1.1
	Small	84.5^{b} ± 1.7	80.8^{b} ± 0.8	74.0^{a} ± 1.4
	Average	83.8^{b} ± 1.5	82.9^{b} ± 0.8	76.2^{a} ± 1.5
	Big	82.7^{b} ± 1.5	84.8^{b} ± 0.7	73.8^{a} ± 1.8
	Huge	84.1^{b} ± 1.4	86.0^{b} ± 0.7	73.5^{a} ± 2.1
J				
	Tiny	79.5^{ab} ± 4.3	78.0^{b} ± 1.4	71.0^{a} ± 1.7
	Small	83.1^{b} ± 2.9	80.3^{b} ± 1.2	68.0^{a} ± 1.9
	Average	83.8^{b} ± 2.5	83.1^{b} ± 1.1	72.1^{a} ± 2.0
	Big	85.5^{b} ± 2.0	85.1^{b} ± 1.0	73.8^{a} ± 2.3
	Huge	81.9^{b} ± 1.6	83.3^{b} ± 1.1	71.9^{a} ± 3.1

Values within a row with different superscripts differ at the 95% confidence interval. F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix V. Table 6. Predicted 21-day calving rate ± SEM to calving as three-year-old (C21_3yo) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		C21_3yo		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	59.2 ± 2.0	60.3 ± 0.8	62.3 ± 1.0
	Small	59.8 ± 2.4	59.2 ± 0.8	60.9 ± 1.2
	Average	60.1 ± 2.5	59.6 ± 0.8	62.7 ± 1.2
	Big	53.5^{a} ± 2.8	60.7^{b} ± 0.8	63.5^{b} ± 1.3
	Huge	59.0 ± 2.5	60.5 ± 0.8	61.4 ± 1.5
FX				
	Tiny	60.7 ± 1.7	62.7 ± 0.7	64.0 ± 0.9
	Small	59.7 ± 1.8	62.8 ± 0.7	64.7 ± 1.0
	Average	57.2^{a} ± 1.9	62.0^{ab} ± 0.7	63.6^{b} ± 1.2
	Big	59.0^{a} ± 2.1	62.1^{ab} ± 0.7	65.8^{b} ± 1.2
	Huge	63.4 ± 2.1	62.4 ± 0.7	65.0 ± 1.3
FJ				
	Tiny	61.9 ± 2.2	63.1 ± 0.8	65.0 ± 1.0
	Small	57.7^{a} ± 2.0	63.9^{b} ± 0.8	65.8^{b} ± 1.2
	Average	61.9 ± 2.1	63.3 ± 0.8	63.3 ± 1.4
	Big	59.2 ± 2.1	64.5 ± 0.8	65.6 ± 1.6
	Huge	63.1 ± 2.1	63.3 ± 0.8	63.7 ± 1.7
JX				
	Tiny	59.8 ± 3.1	60.7 ± 1.1	63.1 ± 1.3
	Small	60.7 ± 2.7	64.2 ± 1.1	67.2 ± 1.7
	Average	57.0^{a} ± 2.5	64.3^{b} ± 1.1	63^{ab} ± 1.9
	Big	60.3 ± 2.5	62.4 ± 1.1	66.1 ± 2.1
	Huge	59.8 ± 2.3	62.5 ± 1.1	67.3 ± 2.3
J				
	Tiny	56.7 ± 6.1	63.7 ± 1.8	67.1 ± 1.8
	Small	62.6 ± 4.5	61.8 ± 1.7	64.1 ± 2.1
	Average	58.8 ± 4.5	62.9 ± 1.6	65.0 ± 2.4
	Big	65.3 ± 3.4	59.8 ± 1.6	60.7 ± 2.7
	Huge	62.2 ± 2.3	62.2 ± 1.7	67.1 ± 3.3

Values within a row with different superscripts differ at the 95% confidence interval. F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix V. Table 7. Predicted 21-day calving rate ± SEM to calving as four-year-old (C21_4yo) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		C21_4yo		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	53.7 ± 2.5	57.1 ± 0.9	59.9 ± 1.2
	Small	56.3 ± 2.8	56.4 ± 0.9	58.4 ± 1.4
	Average	56.0 ± 3.0	57.8 ± 0.9	59.8 ± 1.4
	Big	53.4 ± 3.3	57.4 ± 0.9	60.1 ± 1.5
	Huge	51.4 ± 2.8	57.4 ± 1.0	58.4 ± 1.8
FX				
	Tiny	53.2^{a} ± 2.1	59.1^{b} ± 0.8	59.9^{b} ± 1.0
	Small	57.5 ± 2.3	59.8 ± 0.8	60.7 ± 1.2
	Average	55.7 ± 2.2	60.0 ± 0.8	60.4 ± 1.3
	Big	57.6 ± 2.5	59.6 ± 0.8	62.5 ± 1.4
	Huge	54.6 ± 2.8	59.1 ± 0.8	59.2 ± 1.6
FJ				
	Tiny	56.6 ± 2.7	59.7 ± 1.0	61.8 ± 1.2
	Small	56.1 ± 2.4	61.9 ± 0.9	61.7 ± 1.5
	Average	61.4 ± 2.4	61.4 ± 0.9	62.9 ± 1.6
	Big	61.1 ± 2.5	61.5 ± 0.9	59.2 ± 1.8
	Huge	61.6 ± 2.6	61.6 ± 0.9	60.5 ± 2.0
JX				
	Tiny	58.7 ± 3.7	59.8 ± 1.2	60.1 ± 1.5
	Small	59.0 ± 3.1	62.3 ± 1.2	62.7 ± 1.9
	Average	55.9 ± 2.9	63.3 ± 1.2	63.2 ± 2.1
	Big	58.4 ± 3.0	61.5 ± 1.2	61.6 ± 2.4
	Huge	55.7 ± 2.9	59.7 ± 1.3	54.7 ± 2.8
J				
	Tiny	59.7 ± 6.5	61.6 ± 2.1	64.2 ± 2.1
	Small	63.9 ± 5.1	59.3 ± 1.9	57.9 ± 2.4
	Average	55.2 ± 5.3	62.2 ± 1.8	55.5 ± 2.8
	Big	57.7 ± 4.3	63.1 ± 1.8	50.5 ± 3.3
	Huge	62.9 ± 3.1	59.2 ± 2.0	56.4 ± 4.2

Values within a row with different superscripts differ at the 95% confidence interval.
F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

8.1.4 Re-calving Rate

Appendix V. Table 8. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at six months of age on re-calving rate within 21 days of planned start of calving (RC21) for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers that calved as two-year-old (RC21_2yo), three-year-old (RC21_3yo) or four-year-olds (RC21_4yo).

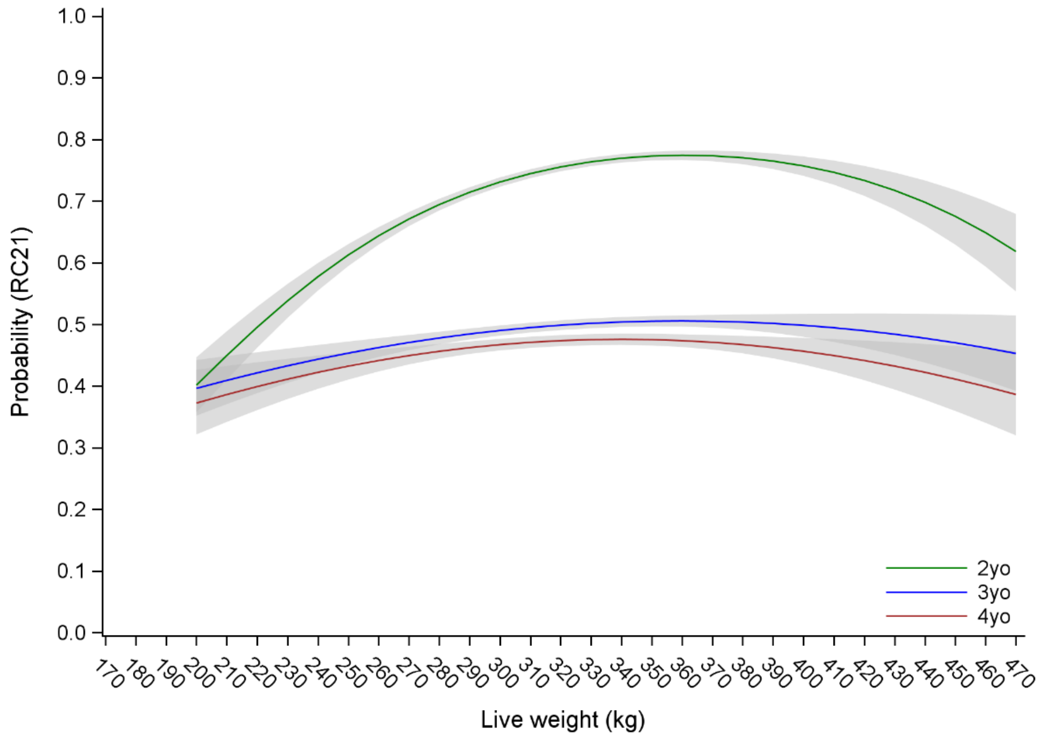
	Intercept	P-value	Linear	P-value	Quadratic	P-value
RC21_2yo						
F	-1.44 ± 0.40	<0.001	0.026 ± 0.005	<0.001	-0.00007 ± 0.00002	<0.001
FX	-1.90 ± 0.35	<0.001	0.035 ± 0.005	<0.001	-0.00010 ± 0.00002	<0.001
FJ	-1.58 ± 0.43	<0.001	0.032 ± 0.006	<0.001	-0.00009 ± 0.00002	<0.001
JX	-1.04 ± 0.55	0.057	0.027 ± 0.007	<0.001	-0.00008 ± 0.00003	0.001
J	0.49 ± 0.77	0.519	0.006 ± 0.011	0.599	-0.00002 ± 0.00004	0.643
RC21_3yo						
F	-1.48 ± 0.38	<0.001	0.016 ± 0.005	0.001	-0.00004 ± 0.00002	0.002
FX	-0.52 ± 0.34	0.122	0.007 ± 0.004	0.129	-0.00002 ± 0.00001	0.246
FJ	-1.78 ± 0.41	<0.001	0.024 ± 0.005	<0.001	-0.00007 ± 0.00002	<0.001
JX	-1.2 ± 0.52	0.021	0.016 ± 0.007	0.025	-0.00005 ± 0.00002	0.052
J	-1.37 ± 0.72	0.055	0.018 ± 0.010	0.081	-0.00005 ± 0.00004	0.148
RC21_4yo						
F	-1.52 ± 0.45	0.001	0.016 ± 0.005	0.003	-0.00005 ± 0.00002	0.005
FX	-0.38 ± 0.39	0.342	0.003 ± 0.005	0.512	-0.00001 ± 0.00002	0.686
FJ	-1.48 ± 0.48	0.002	0.020 ± 0.006	0.002	-0.00006 ± 0.00002	0.003
JX	-1.68 ± 0.60	0.005	0.023 ± 0.008	0.006	-0.00007 ± 0.00003	0.009
J	-1.45 ± 0.82	0.077	0.021 ± 0.012	0.071	-0.00008 ± 0.00004	0.066

Appendix V. Table 9. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at 12 months of age on re-calving rate within 21 days of planned start of calving (RC21) for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers that calved as two-year-old (RC21_2yo), three-year-old (RC21_3yo) or four-year-old (RC21_4yo)

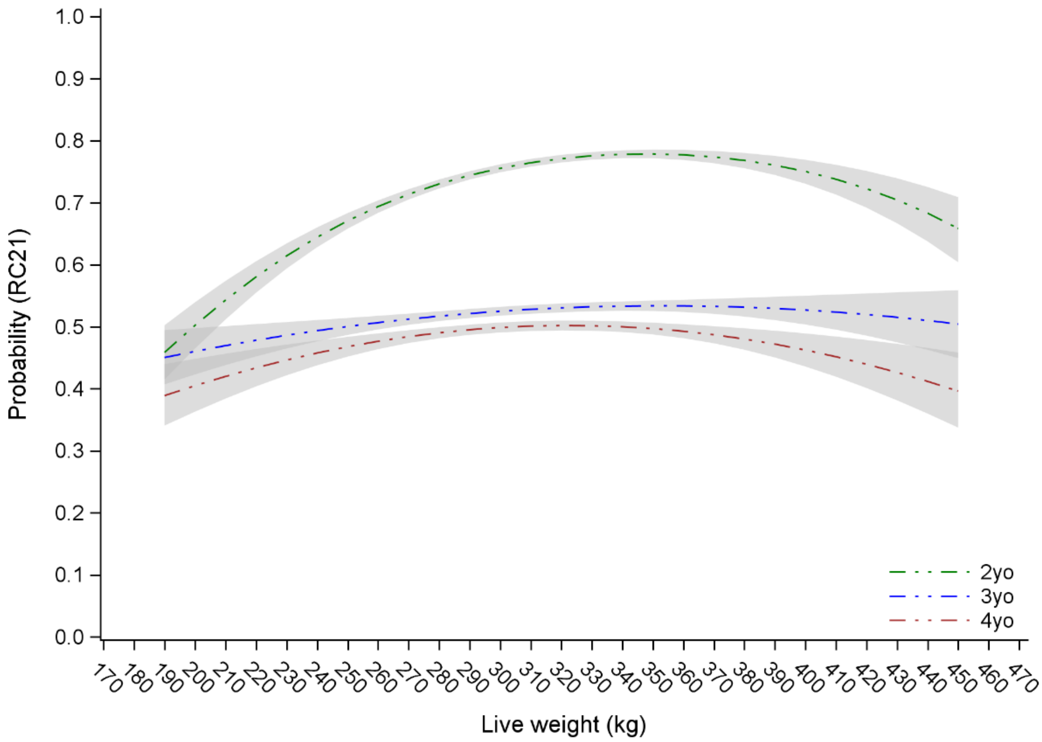
	Intercept	P-value	Linear	P-value	Quadratic	P-value
RC21_2yo						
F	-5.28 ± 0.50	<0.001	0.047 ± 0.004	<0.001	-0.00008 ± 0.00001	<0.001
FX	-4.60 ± 0.45	<0.001	0.044 ± 0.004	<0.001	-0.00008 ± 0.00001	<0.001
FJ	-4.83 ± 0.56	<0.001	0.048 ± 0.005	<0.001	-0.00010 ± 0.00001	<0.001
JX	-3.77 ± 0.76	<0.001	0.042 ± 0.007	<0.001	-0.00009 ± 0.00001	<0.001
J	-2.45 ± 1.17	0.036	0.032 ± 0.011	0.003	-0.00008 ± 0.00003	0.002
RC21_3yo						
F	-1.76 ± 0.50	<0.001	0.012 ± 0.004	0.003	-0.00002 ± 0.00001	0.012
FX	-0.98 ± 0.44	0.027	0.007 ± 0.004	0.046	-0.00001 ± 0.00001	0.127
FJ	-2.69 ± 0.56	<0.001	0.022 ± 0.005	<0.001	-0.00004 ± 0.00001	<0.001
JX	-2.31 ± 0.75	0.002	0.019 ± 0.007	0.004	-0.00003 ± 0.00001	0.014
J	-1.11 ± 1.12	0.319	0.009 ± 0.01	0.399	-0.00001 ± 0.00002	0.532
RC21_4yo						
F	-2.43 ± 0.60	<0.001	0.017 ± 0.005	<0.001	-0.00003 ± 0.00001	0.001
FX	-1.82 ± 0.52	0.001	0.014 ± 0.004	0.001	-0.00002 ± 0.00001	0.004
FJ	-2.10 ± 0.65	0.001	0.018 ± 0.005	0.001	-0.00004 ± 0.00001	0.002
JX	-3.14 ± 0.86	<0.001	0.027 ± 0.008	<0.001	-0.00006 ± 0.00002	0.001
J	-3.40 ± 1.35	0.012	0.033 ± 0.012	0.009	-0.00008 ± 0.00003	0.006

Appendix V. Table 10. Intercept and regression coefficients (± SEM) for the linear and quadratic effect of live weight (LWT) at 15 months of age on re-calving rate within 21 days of planned start of calving (RC21) for Holstein-Friesian (F), Holstein-Friesian crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ), Jersey crossbred (JX) or Jersey (J) heifers that calved as two-year-old (RC21_2yo), three-year-old (RC21_3yo) or four-year-old (RC21_4yo)

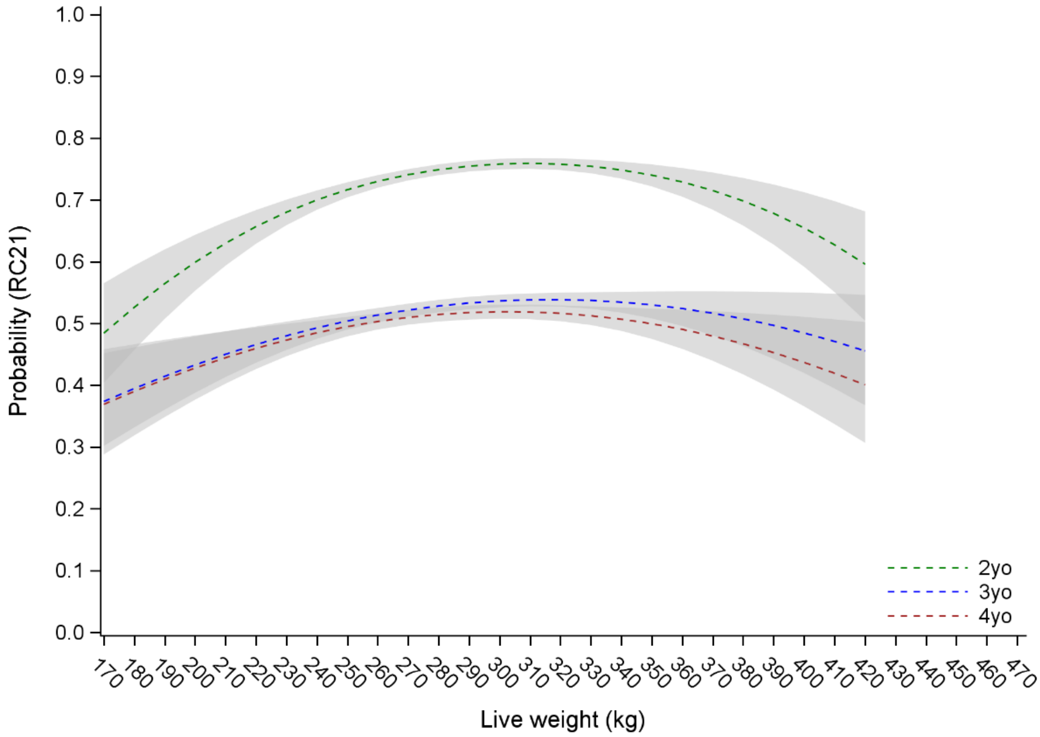
	Intercept	P-value	Linear	P-value	Quadratic	P-value
RC21_2yo						
F	-6.98 ± 0.63	<0.001	0.046 ± 0.004	<0.001	-0.00006 ± 0.00001	<0.001
FX	-5.66 ± 0.58	<0.001	0.040 ± 0.004	<0.001	-0.00006 ± 0.00001	<0.001
FJ	-6.36 ± 0.72	<0.001	0.047 ± 0.005	<0.001	-0.00007 ± 0.00001	<0.001
JX	-4.80 ± 0.95	<0.001	0.038 ± 0.007	<0.001	-0.00006 ± 0.00001	<0.001
J	-2.81 ± 1.48	0.057	0.027 ± 0.011	0.013	-0.00005 ± 0.00002	0.015
RC21_3yo						
F	-2.22 ± 0.63	<0.001	0.013 ± 0.004	0.001	-0.00002 ± 0.00001	0.003
FX	-1.43 ± 0.57	0.013	0.009 ± 0.004	0.015	-0.00001 ± 0.00001	0.031
FJ	-3.72 ± 0.72	<0.001	0.024 ± 0.005	<0.001	-0.00004 ± 0.00001	<0.001
JX	-2.97 ± 0.94	0.002	0.020 ± 0.006	0.002	-0.00003 ± 0.00001	0.005
J	-1.16 ± 1.39	0.405	0.008 ± 0.010	0.450	-0.00001 ± 0.00002	0.533
RC21_4yo						
F	-2.60 ± 0.75	0.001	0.015 ± 0.005	0.001	-0.00002 ± 0.00001	0.002
FX	-2.72 ± 0.67	<0.001	0.017 ± 0.004	<0.001	-0.00003 ± 0.00001	<0.001
FJ	-2.08 ± 0.83	0.012	0.014 ± 0.005	0.012	-0.00002 ± 0.00001	0.016
JX	-3.11 ± 1.07	0.004	0.021 ± 0.007	0.004	-0.00003 ± 0.00001	0.006
J	-4.64 ± 1.64	0.005	0.035 ± 0.012	0.003	-0.00007 ± 0.00002	0.003



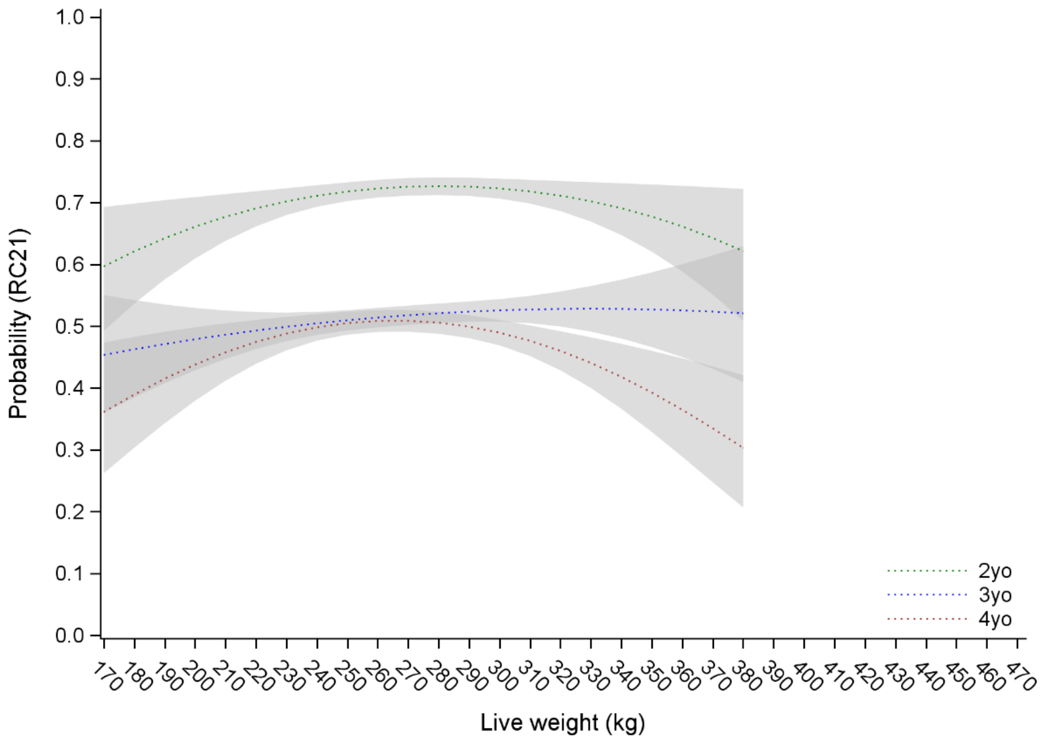
Appendix V. Figure 9. Relationship between live weight (LWT) at 15 months of age and re-calving rate within 21 days planned start of calving (RC21) for Holstein-Friesian (F) heifers that calved that year as two- (2yo), three- (3yo) or four-year-olds (4yo).



Appendix V. Figure 10. Relationship between live weight (LWT) at 15 months of age and re-calving rate within 21 days planned start of calving (RC21) for Holstein-Friesian crossbred (FX) heifers that calved that year as two- (2yo), three- (3yo) or four-year-olds (4yo).



Appendix V. Figure 11. Relationship between live weight (LWT) at 15 months of age and re-calving rate within 21 days planned start of calving (RC21) for Jersey crossbred (JX) heifers that calved that year as two- (2yo), three- (3yo) or four-year-olds (4yo).

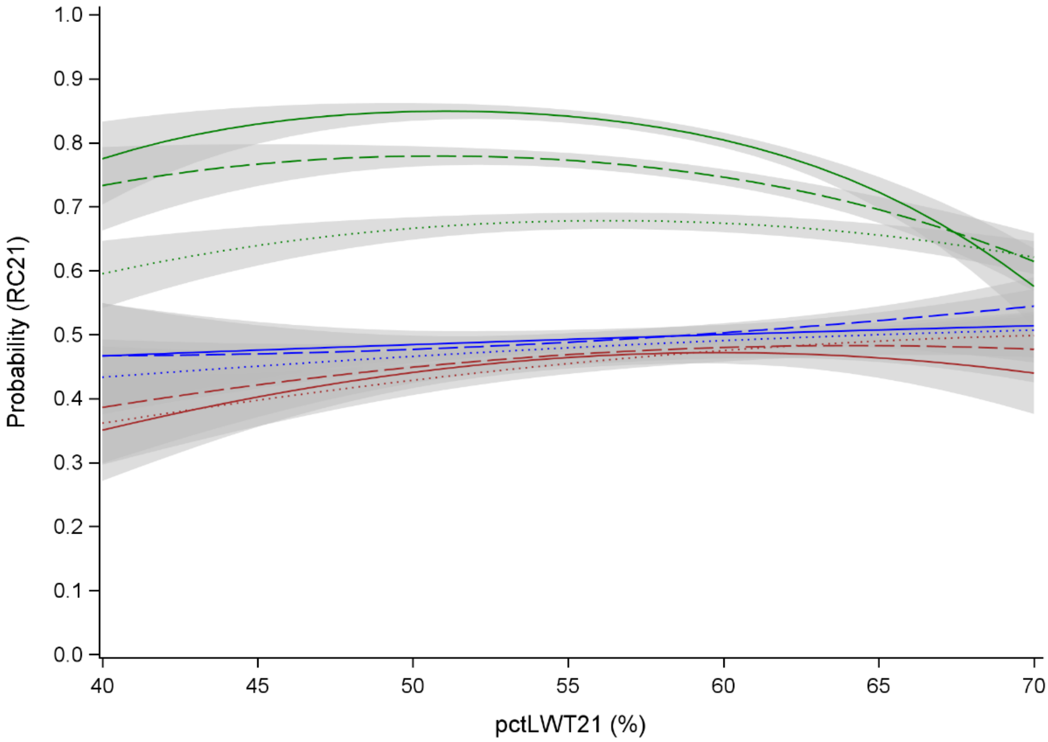


Appendix V. Figure 12. Relationship between live weight (LWT) at 15 months of age and re-calving rate within 21 days planned start of calving (RC21) for Jersey (J) heifers that calved that year as two- (2yo), three- (3yo) or four-year-olds (4yo).

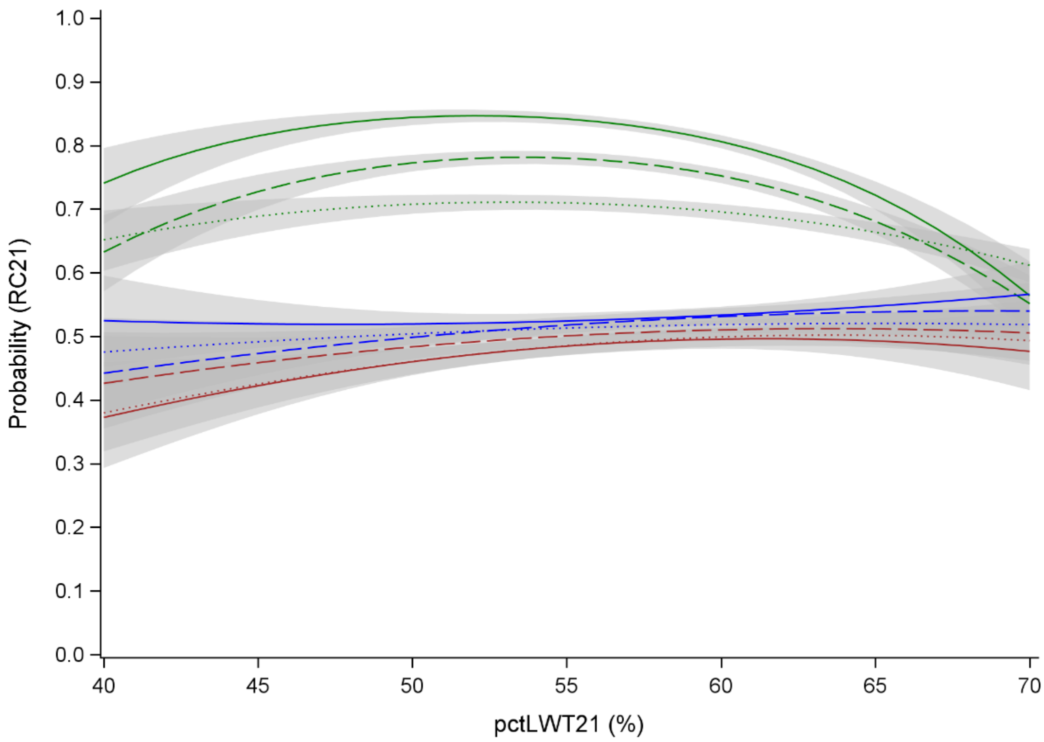
Appendix V. Table 11. Least-squares means ± SEM of 21-day re-calving rate (RC21) of Holstein-Friesian (F), Holstein-Friesian-crossbred (FX), Holstein-Friesian-Jersey crossbred (FJ) Jersey crossbred (JX) and Jersey (J) heifers that were tiny, small, average, big or huge at 21 months of age.

Breed and LWT rank	RC21_2yo	RC21_3yo	RC21_4yo
F			
Tiny	$66.3^{a} \pm 0.6$	$46.7^{a} \pm 0.6$	44.2 ± 0.7
Small	$72.2^{b} \pm 0.6$	$47.4^{ab} \pm 0.6$	44.4 ± 0.7
Average	$75.2^{c} \pm 0.5$	$48.7^{bc} \pm 0.6$	44.7 ± 0.7
Big	$77.5^{d} \pm 0.5$	$49.4^{c} \pm 0.6$	45.5 ± 0.7
Huge	$81.7^{e} \pm 0.5$	$48.9^{bc} \pm 0.6$	43.9 ± 0.7
FX			
Tiny	$69^{a} \pm 0.5$	$49.9^{a} \pm 0.6$	$46.7^{ab} \pm 0.6$
Small	$73.1^{b} \pm 0.5$	$51.5^{b} \pm 0.5$	$47.9^{b} \pm 0.6$
Average	$75.1^{c} \pm 0.5$	$51.1^{ab} \pm 0.5$	$48^{b} \pm 0.6$
Big	$77.8^{d} \pm 0.5$	$51.7^{b} \pm 0.5$	$47.9^{b} \pm 0.6$
Huge	$81.6^{e} \pm 0.4$	$52.3^{b} \pm 0.6$	$46.3^{a} \pm 0.6$
FJ			
Tiny	$68.3^{a} \pm 0.6$	$50.3^{a} \pm 0.7$	$48.1^{a} \pm 0.7$
Small	$73.7^{b} \pm 0.6$	$52.7^{b} \pm 0.7$	$50.3^{b} \pm 0.7$
Average	$74.1^{b} \pm 0.6$	$52.4^{b} \pm 0.6$	$50.3^{b} \pm 0.7$
Big	$76.9^{c} \pm 0.5$	$54^{b} \pm 0.6$	$49.6^{ab} \pm 0.7$
Huge	$79.9^{d} \pm 0.5$	$53.2^{b} \pm 0.6$	$49.3^{ab} \pm 0.7$
JX			
Tiny	$69.3^{a} \pm 0.8$	$48.6^{a} \pm 0.9$	$47.7^{ab} \pm 1$
Small	$73.1^{b} \pm 0.7$	$52.9^{b} \pm 0.8$	$50.1^{b} \pm 0.9$
Average	$74.9^{bc} \pm 0.7$	$52.6^{b} \pm 0.8$	$50.3^{b} \pm 0.9$
Big	$75.4^{c} \pm 0.7$	$51.4^{b} \pm 0.8$	$50.5^{b} \pm 0.9$
Huge	$78.1^{d} \pm 0.7$	$51.3^{b} \pm 0.8$	$46.2^{a} \pm 0.9$
J			
Tiny	$68.2^{a} \pm 1.3$	48.9 ± 1.3	48 ± 1.5
Small	$69.7^{a} \pm 1.2$	50.4 ± 1.3	45.7 ± 1.4
Average	$73.7^{bc} \pm 1.1$	50.7 ± 1.2	48.6 ± 1.4
Big	$74.5^{c} \pm 1.1$	49.9 ± 1.2	47.4 ± 1.4
Huge	$71.1^{ab} \pm 1.1$	51.1 ± 1.3	47.1 ± 1.5

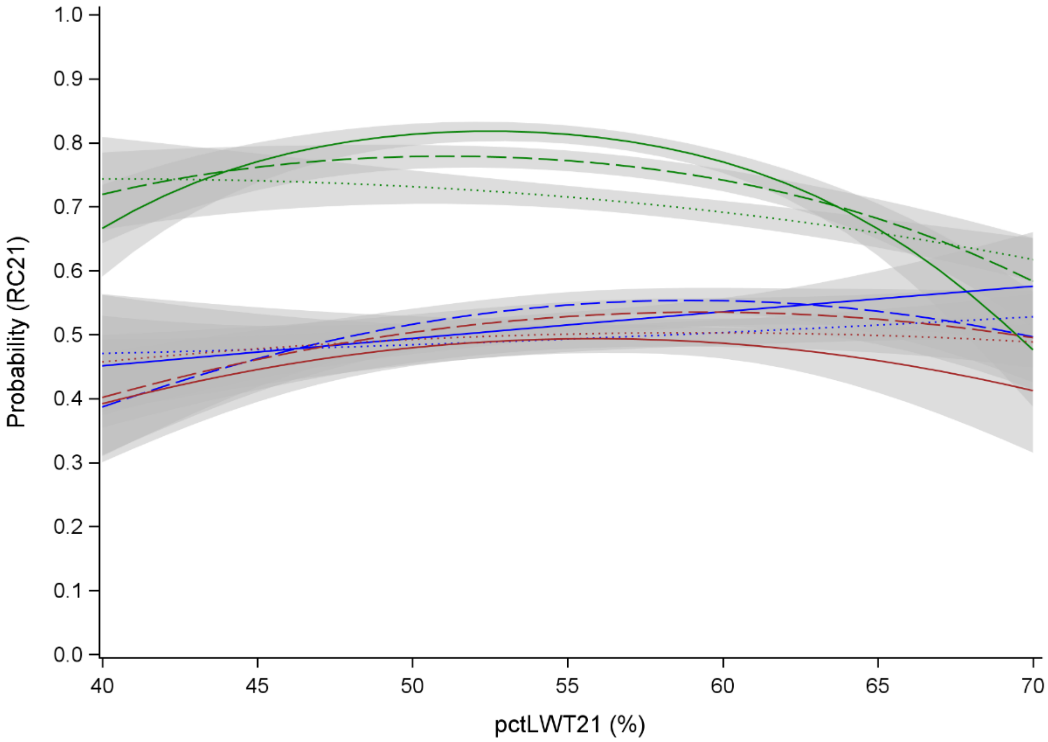
$^{a-d}$Values within column and breed group with different superscripts differ between LWT categories (P<0.05). Where C2yo is first calving as a two-year-old, C3yo is second calving as a three-year-old, and C4yo is third calving as a four-year-old.



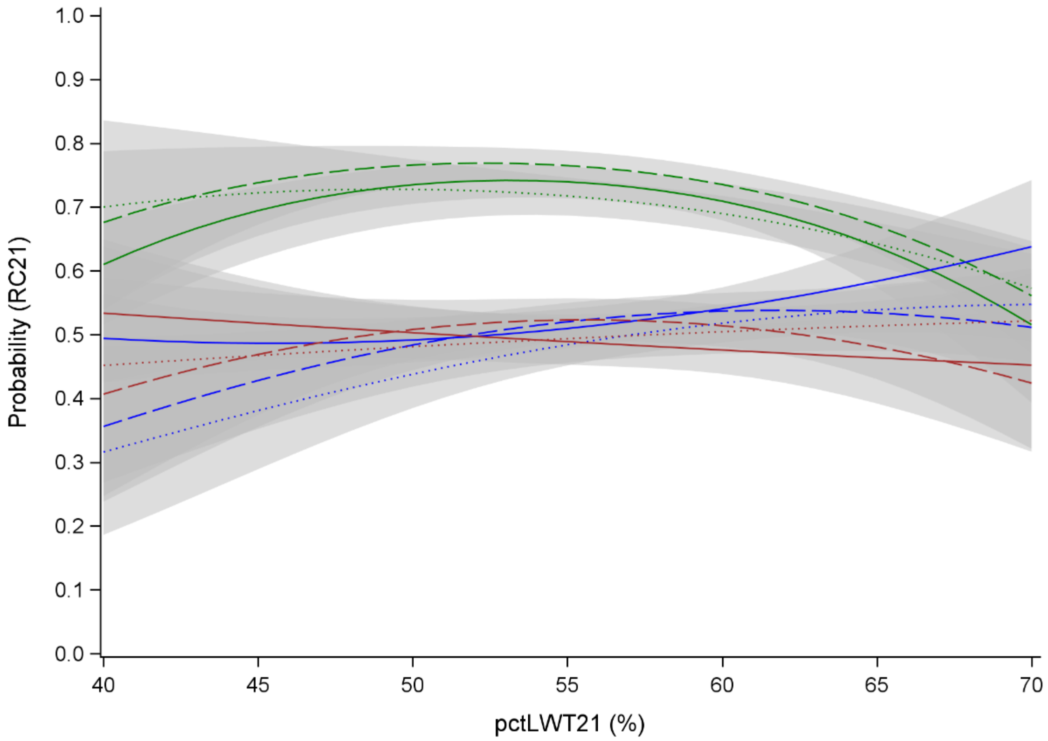
Appendix V. Figure 13. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of re-calving within 21 days of planned start of calving (RC21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Holstein-Friesian (F) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.



Appendix V. Figure 14. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of re-calving within 21 days of planned start of calving (RC21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Holstein-Friesian crossbred (FX) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.



Appendix V. Figure 15. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of re-calving within 21 days of planned start of calving (RC21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Jersey crossbred (JX) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.



Appendix V. Figure 16. Relationship between percentage of 21-month live weight at 12 months of age (pctLWT21) and probability of re-calving within 21 days of planned start of calving (RC21) as a two-year-old (green lines), three-year-old (blue lines) or four-year-old (red lines) for Jersey (J) heifers that were tiny (dotted lines), average (dashed lines) or huge (solids lines) in LWT at 21 months of age. Shaded area indicates 95% confidence intervals.

Appendix V. Table 12. Predicted 21-day calving rate ± SEM to calving as two-year-old (C21_2yo) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		C21_2yo		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	63.9 ± 1.6	67.8 ± 0.7	65.6 ± 0.9
	Small	71.1^{ab} ± 1.6	74.8^{b} ± 0.6	66.6^{a} ± 1.0
	Average	76.6^{b} ± 1.7	77.3^{b} ± 0.6	69.5^{a} ± 1.0
	Big	79.7^{b} ± 1.7	79.8^{b} ± 0.6	70.5^{a} ± 1.1
	Huge	82.9^{b} ± 1.5	84.1^{b} ± 0.5	72.3^{a} ± 1.2
FX				
	Tiny	68.9^{ab} ± 1.3	71.0^{b} ± 0.6	66.4^{a} ± 0.8
	Small	71.5^{a} ± 1.4	75.8^{b} ± 0.5	67.2^{a} ± 0.9
	Average	72.7^{a} ± 1.4	78.0^{b} ± 0.5	68.1^{a} ± 1.0
	Big	75.9^{b} ± 1.5	80.1c ± 0.5	70.8^{a} ± 1.0
	Huge	81.5^{b} ± 1.3	84.1^{b} ± 0.4	72.2^{a} ± 1.1
FJ				
	Tiny	69.6^{ab} ± 1.7	71.0^{b} ± 0.7	64.4^{a} ± 0.9
	Small	74.0^{b} ± 1.5	76.4^{b} ± 0.6	67.4^{a} ± 1.1
	Average	70.1^{a} ± 1.6	77.0^{b} ± 0.6	67.9^{a} ± 1.3
	Big	74.9^{b} ± 1.5	79.9c ± 0.6	67.8^{a} ± 1.4
	Huge	81.0^{b} ± 1.3	82.2^{b} ± 0.6	70.5^{a} ± 1.5
JX				
	Tiny	74.0^{b} ± 2.3	71.5^{b} ± 0.9	65.9^{a} ± 1.2
	Small	76.0^{b} ± 2.0	75.5^{b} ± 0.8	66.7^{a} ± 1.4
	Average	76.2^{b} ± 1.7	77.2^{b} ± 0.8	68.1^{a} ± 1.6
	Big	73.5^{b} ± 1.8	78.5c ± 0.8	66.1^{a} ± 1.8
	Huge	77.0^{b} ± 1.6	81.3^{b} ± 0.7	66.5^{a} ± 2.1
J				
	Tiny	72.2^{ab} ± 4.8	71.7^{b} ± 1.5	64.3^{a} ± 1.7
	Small	76.5^{b} ± 3.4	74.0^{b} ± 1.3	61.2^{a} ± 1.9
	Average	73.8^{ab} ± 3.1	76.5^{b} ± 1.2	67.1^{a} ± 2.0
	Big	73.9^{ab} ± 2.5	76.8^{b} ± 1.2	67.8^{a} ± 2.3
	Huge	69.5^{ab} ± 2.0	74.0^{b} ± 1.3	63.8^{a} ± 3.1

Values within a row with different superscripts differ at the 95% confidence interval. F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix V. Table 13. Predicted 21-day calving rate ± SEM to calving as three-year-old (C21_3yo) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		C21_3yo		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	44.6 ± 1.8	47.5 ± 0.7	49.6 ± 1.0
	Small	44.0^{a} ± 2.1	47.2^{ab} ± 0.7	50.7^{b} ± 1.1
	Average	46.6 ± 2.3	48.4 ± 0.7	51.8 ± 1.1
	Big	39.8^{a} ± 2.3	49.3^{b} ± 0.7	52.9^{b} ± 1.2
	Huge	47.1 ± 2.2	48.8 ± 0.8	50.3 ± 1.4
FX				
	Tiny	48.7 ± 1.6	50.9 ± 0.6	51.6 ± 0.8
	Small	47.5^{a} ± 1.7	52.1^{ab} ± 0.6	53.8^{b} ± 1.0
	Average	46.9^{a} ± 1.7	51.3^{ab} ± 0.6	53.4^{b} ± 1.1
	Big	47.9^{a} ± 1.9	51.2^{a} ± 0.6	55.5^{b} ± 1.2
	Huge	51.5 ± 1.9	52.0 ± 0.6	54.3 ± 1.3
FJ				
	Tiny	47.3^{a} ± 2.0	50.7^{ab} ± 0.8	53.7^{b} ± 1.0
	Small	46.3^{a} ± 1.9	53^{b} ± 0.8	55.9^{b} ± 1.2
	Average	49.0 ± 1.9	52.8 ± 0.8	54.4 ± 1.4
	Big	47.4^{a} ± 1.9	54.1^{b} ± 0.8	56.6^{b} ± 1.5
	Huge	50.9 ± 1.9	53.2 ± 0.8	54.2 ± 1.6
JX				
	Tiny	47.2 ± 2.8	48.9 ± 1.0	51.1 ± 1.2
	Small	49.2 ± 2.5	53.7 ± 1.0	54.9 ± 1.6
	Average	45.8^{a} ± 2.2	54.2^{b} ± 1.0	53.2^{ab} ± 1.8
	Big	45.4^{a} ± 2.2	51.4^{ab} ± 1.0	56.1^{b} ± 2.0
	Huge	46.8 ± 2.1	51.1 ± 1.0	55.2 ± 2.3
J				
	Tiny	37.7^{a} ± 5.0	48.0^{ab} ± 1.7	53.5^{b} ± 1.8
	Small	48.7 ± 4.1	50.3 ± 1.5	54.2 ± 2.0
	Average	42.4 ± 3.8	51.6 ± 1.5	53.0 ± 2.2
	Big	51.9 ± 3.2	49.8 ± 1.5	50.4 ± 2.6
	Huge	48.2 ± 2.2	50.6 ± 1.6	58.0 ± 3.3

Values within a row with different superscripts differ at the 95% confidence interval. F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix V. Table 14. Predicted 21-day calving rate ± SEM to calving as four-year-old (C21_4yo) of heifers that were 45%, 55% or 65% of their 21-month live weight (LWT) at 12 months of age (pctLWT21).

Breed group and LWT category		C21_4yo		
		45% LWT21	55% LWT21	65% LWT21
F				
	Tiny	39.1^{a} ± 2.1	44.8^{ab} ± 0.8	48.3^{b} ± 1.1
	Small	43.2 ± 2.4	45.4 ± 0.8	47.9 ± 1.2
	Average	41.5 ± 2.6	46.2 ± 0.8	47.6 ± 1.3
	Big	40.3^{a} ± 2.8	46.3^{ab} ± 0.8	49.3^{b} ± 1.4
	Huge	39.6 ± 2.4	45.8 ± 0.9	45.7 ± 1.6
FX				
	Tiny	41.8^{a} ± 1.9	47.9^{b} ± 0.7	49.5^{b} ± 1.0
	Small	45.6 ± 2.0	48.9 ± 0.7	50.5 ± 1.1
	Average	45.2 ± 2.0	49.4 ± 0.7	50.5 ± 1.2
	Big	45.3^{a} ± 2.2	48.4^{a} ± 0.7	52.7^{b} ± 1.3
	Huge	41.6^{a} ± 2.3	47.8^{b} ± 0.7	48.6^{ab} ± 1.5
FJ				
	Tiny	45.7 ± 2.4	49.0 ± 0.9	50.4 ± 1.1
	Small	46.0^{a} ± 2.2	52.1^{b} ± 0.9	51.3^{ab} ± 1.4
	Average	49.7 ± 2.2	51.5 ± 0.9	52.5 ± 1.5
	Big	49.1 ± 2.3	50.9 ± 0.9	49.8 ± 1.7
	Huge	49.3 ± 2.3	50.5 ± 0.9	50.6 ± 1.9
JX				
	Tiny	47.1 ± 3.3	49.4 ± 1.2	49.2 ± 1.4
	Small	48.4 ± 2.9	50.7 ± 1.1	52.6 ± 1.8
	Average	45.4 ± 2.6	52.2 ± 1.2	51.7 ± 2.0
	Big	45.8 ± 2.6	52.4 ± 1.2	52.4 ± 2.2
	Huge	43.9 ± 2.6	48.7 ± 1.2	45.3 ± 2.6
J				
	Tiny	46.1 ± 6.0	48.7 ± 1.9	50.7 ± 2.0
	Small	47.6 ± 4.6	47.2 ± 1.7	46.5 ± 2.2
	Average	46.2 ± 4.9	51.7 ± 1.7	47.4 ± 2.6
	Big	47.3^{ab} ± 4.0	52.3^{b} ± 1.7	40.4^{a} ± 2.9
	Huge	51.1 ± 2.9	48.2 ± 1.8	45.7 ± 3.7

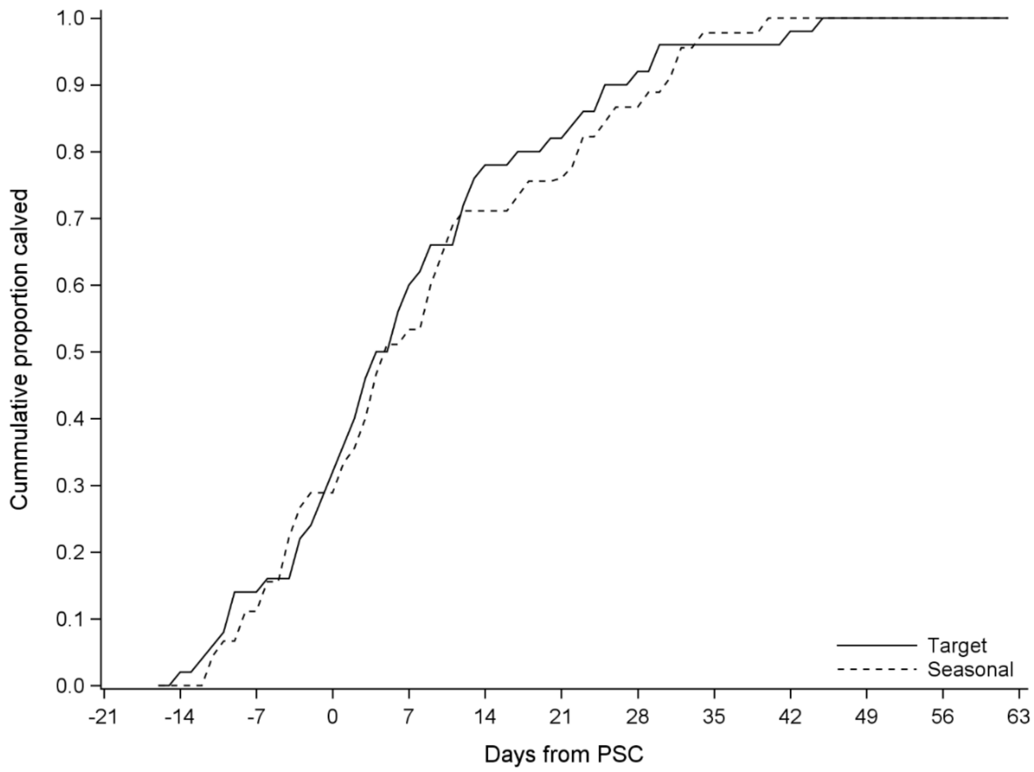
Values within a row with different superscripts differ at the 95% confidence interval. F=Holstein-Friesian, FX=Holstein-Friesian crossbred, FJ=Holstein-Friesian-Jersey crossbred, J=Jersey and JX=Jersey crossbred.

Appendix VI

Appendix VI. Table 1. Least square means and standard errors of regression coefficients of the growth curve modelled with a fourth-order Legendre polynomial fitted to heifers grown "To Target" or in a Seasonal pattern from six to 15 months of age.

	Seasonal	To Target	P-value
a0	311.42[a] ± 3.18	327.10[b] ± 3.15	<0.001
a1	58.98[a] ± 0.80	66.59[b] ± 0.79	<0.001
a2	9.64[b] ± 0.36	3.56[a] ± 0.36	<0.001
a3	5.51[b] ± 0.26	1.09[a] ± 0.26	<0.001
a4	2.35 ± 0.17	2.53 ± 0.17	0.4601

Values with different superscripts within row are significantly different (P<0.001).

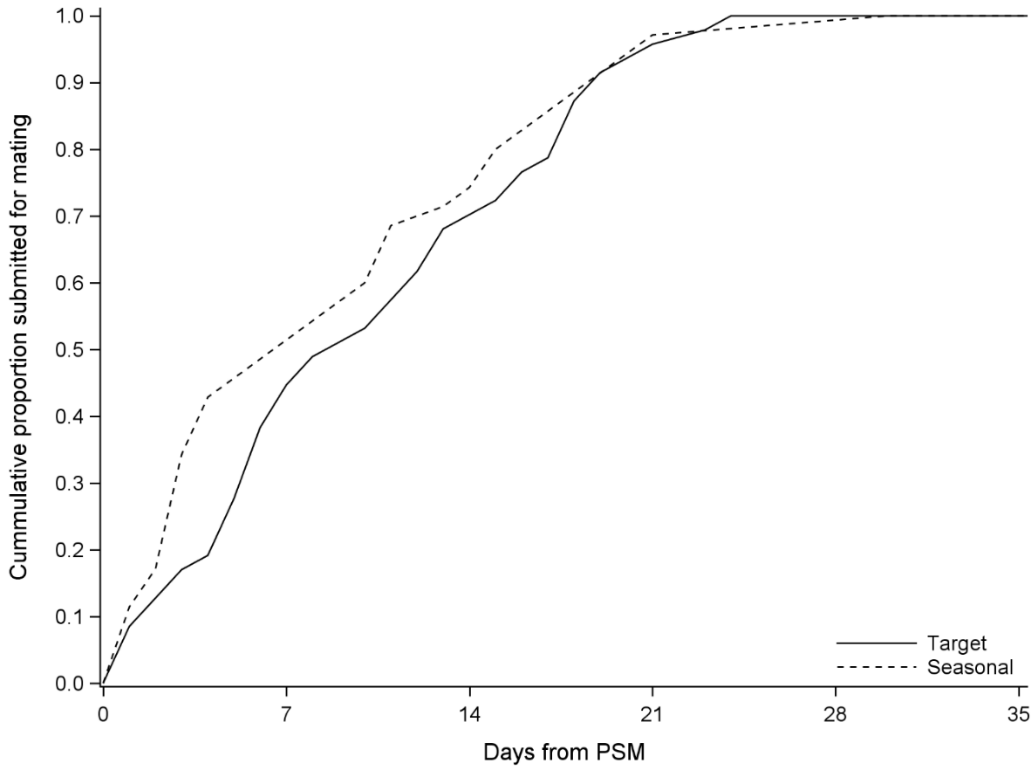


Appendix VI. Figure 1. Cumulative proportion of heifers that calved by days from planned start of calving (PSC) for heifers grown to "Target" or in a Seasonal pattern from six months of age to 15 months of age. (Wilcoxon and log-Rank P>0.05).

Appendix VI. Table 2. Odds ratios (95% CI) of a heifer conceiving in the first cycle, or by the end of the seven-week mating period.

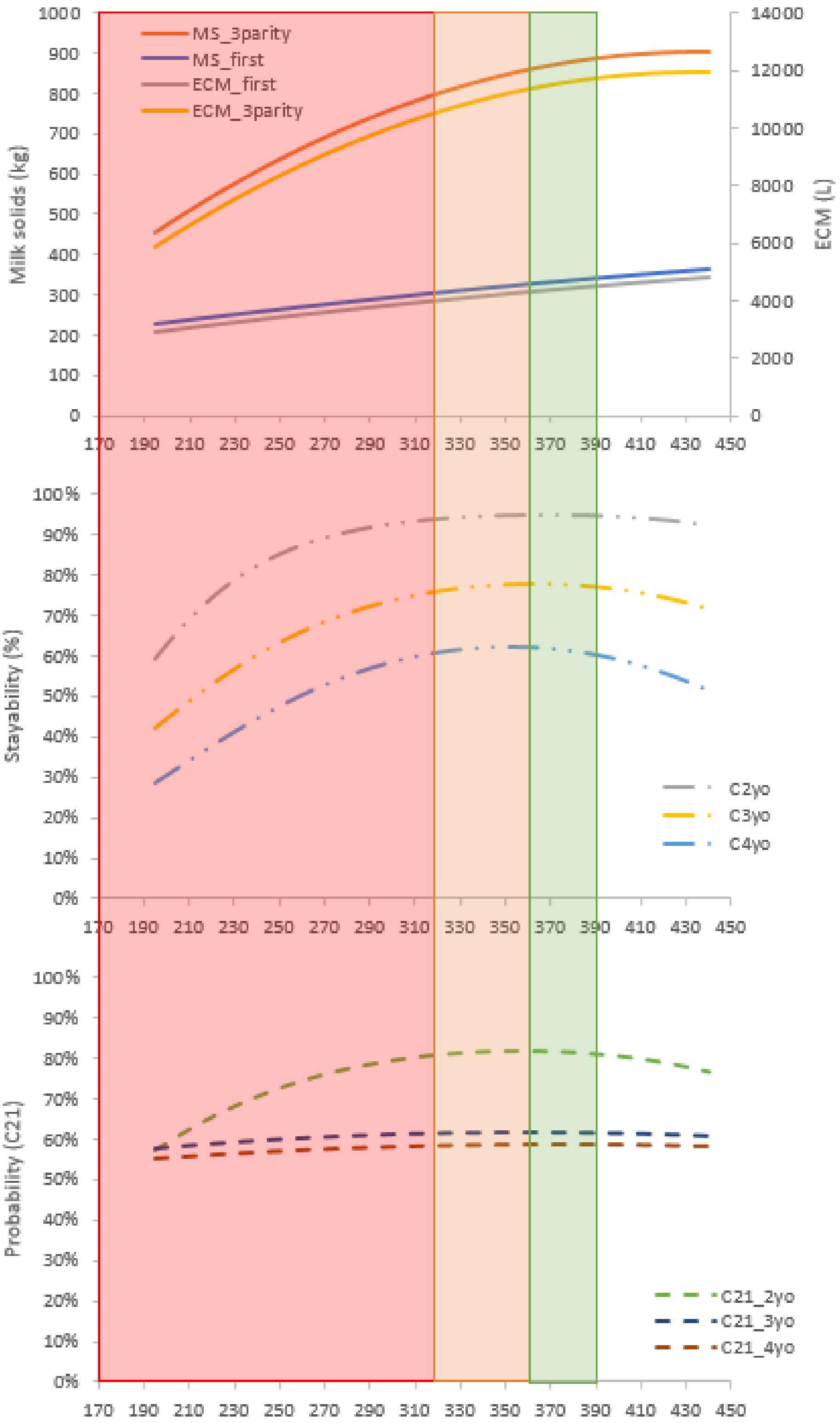
		Preg 1st cycle	P value	Preg by end	P value
Treatment	Seas vs Target	0.865 (0.375 – 2.000)	0.7351	0.462 (0.081 - 2.637)	0.3851
Cycles before PSM	0 cycles vs 3 cycles	0.683 (0.176 - 2.654)			
	1 cycle vs 3 cycles	1.015 (0.311 - 3.309)	0.9544	-*	
	2 cycles vs 3 cycles	0.911 (0.298 – 2.783)			
Age at puberty		0.997 (0.987 - 1.007)	0.5025	1.005 (0.985 - 1.025)	0.6105

*Could not be estimated due to all heifers that had no cycles before PSM becoming pregnant by the end of the mating period.

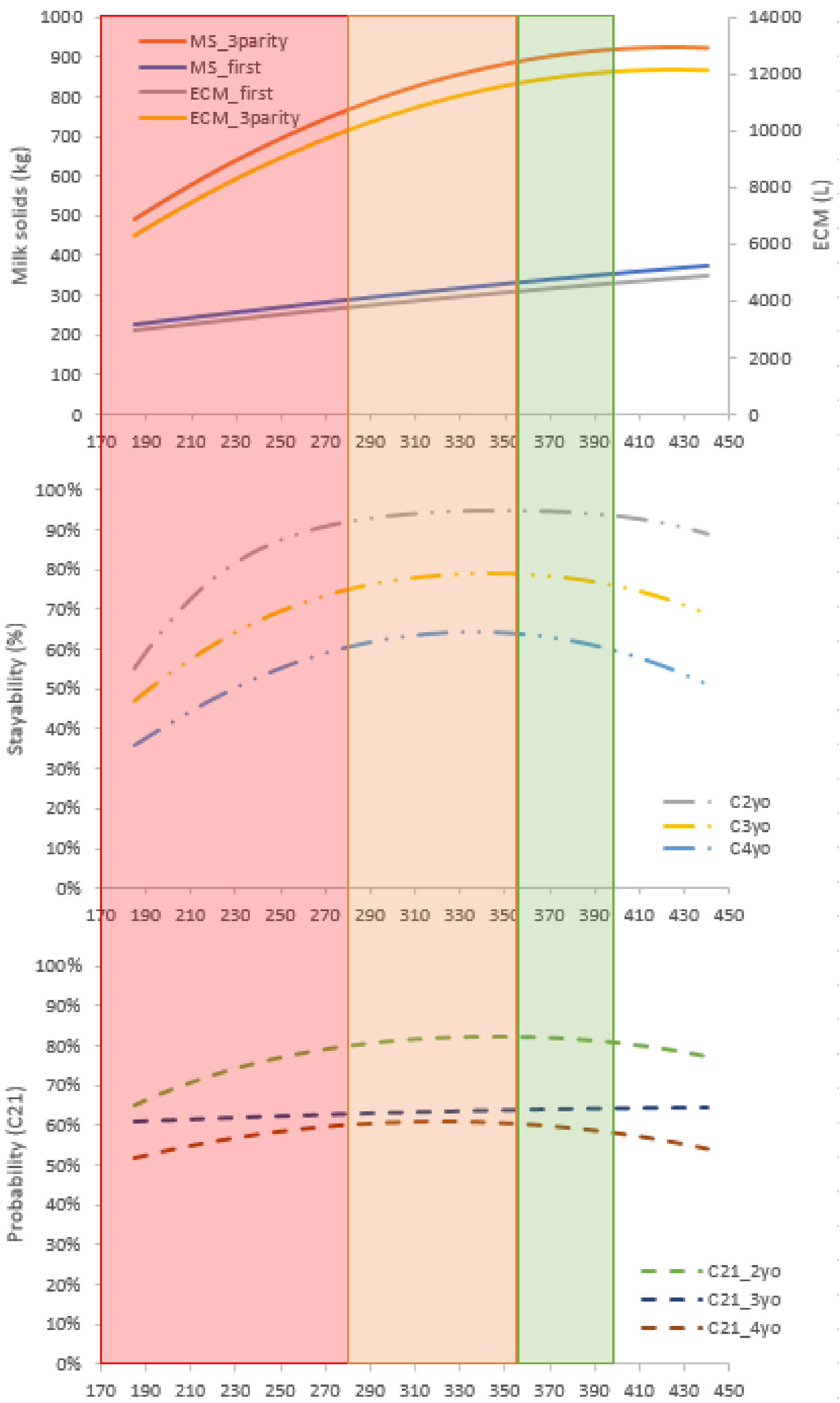


Appendix VI. Figure 2. Cumulative proportion of heifers that were mated during first lactation by days from planned start of mating (PSM2) for heifers grown “Target” or in a Seasonal pattern from six months of age to mating at 15 months of age. (Wilcoxon and log-Rank P>0.05). (Does not include synchronised heifers).

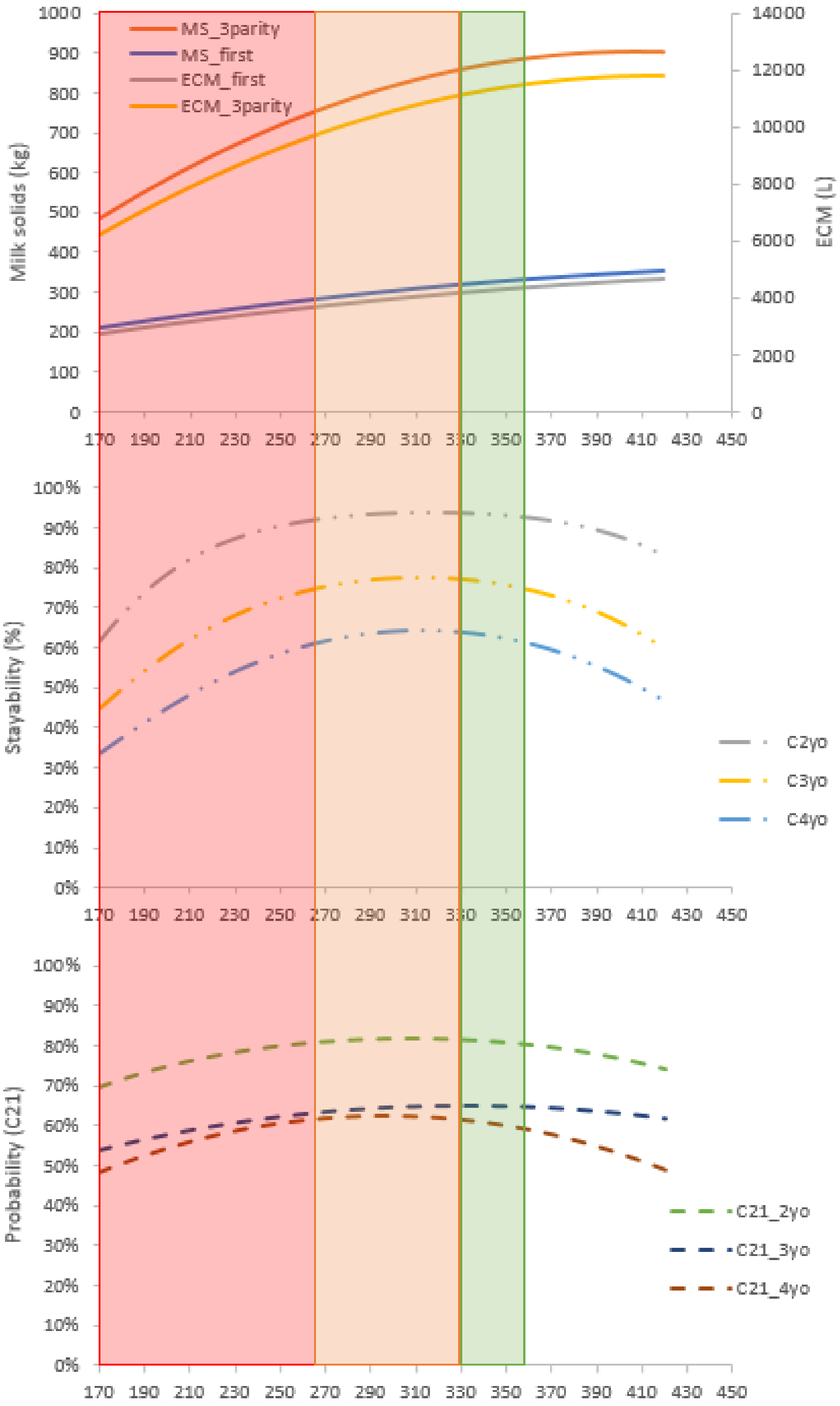
Appendix VII



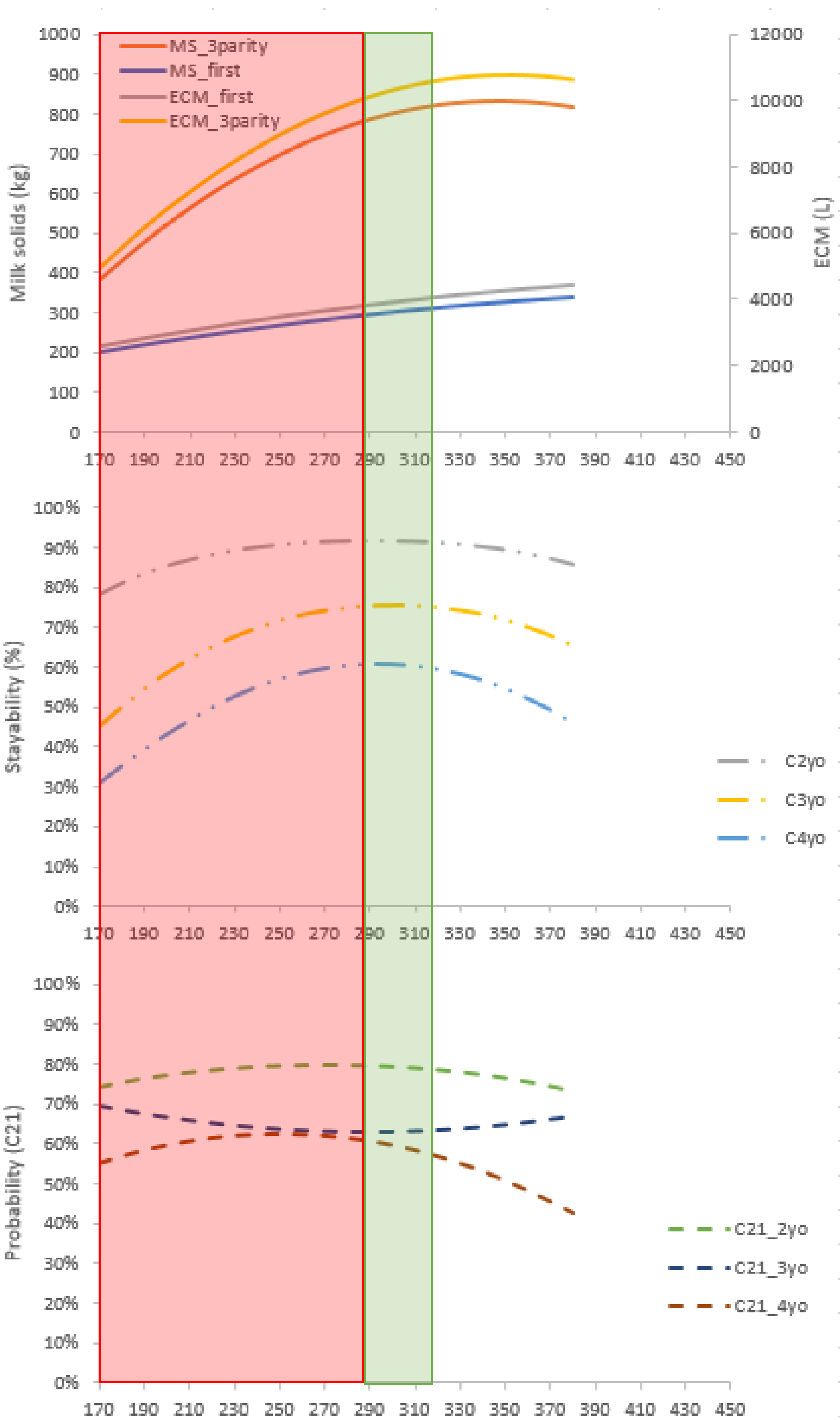
Appendix VII. Figure 1. Relationships between 15-month live weight (LWT) and milk production (milksolids; MS and energy-corrected milk; ECM) and reproduction (stayability and 21-day calving rates; C21) for Holstein-Friesian (F). The LWT range where both reproduction and milk production were poor (red band), reproduction was good, but milk production was poor (orange band), "ideal range" of good reproduction and milk production (green band) and where reproduction declined but milk production was good (white band).



Appendix VII. Figure 2. Relationships between 15-month live weight (LWT) and milk production (milksolids; MS and energy-corrected milk; ECM) and reproduction (stayability and 21-day calving rates; C21) for Holstein-Friesian crossbred (FX). The LWT range where both reproduction and milk production were poor (red band), reproduction was good, but milk production was poor (orange band), "ideal range" of good reproduction and milk production (green band) and where reproduction declined but milk production was good (white band).



Appendix VII. Figure 3. Relationships between 15-month live weight (LWT) and milk production (milksolids; MS and energy-corrected milk; ECM) and reproduction (stayability and 21-day calving rates; C21) for Jersey crossbred (JX). The LWT range where both reproduction and milk production were poor (red band), reproduction was good, but milk production was poor (orange band), "ideal range" of good reproduction and milk production (green band) and where reproduction declined but milk production was good (white band).



Appendix VII. Figure 4. Relationships between 15-month live weight (LWT) and milk production (milksolids; MS and energy-corrected milk; ECM) and reproduction (stayability and 21-day calving rates; C21) for Jersey (J). The LWT range where both reproduction and milk production were poor (red band), "ideal range" of good reproduction and milk production (green band) and where reproduction declined but milk production was good (white band).

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Name of candidate:	Rhiannon Handcock
Name/title of Primary Supervisor:	A/P Rebecca Hickson
Name of Research Output and full reference:	
Handcock RC, Lopez-Villalobos N, McNaughton LR, Edwards GR, Hickson RE 2017. Growth curves of New Zealand Holstein-Friesian, Jersey and Holstein-Friesian-Jersey crossbred heifers Proceedings of the New Zealand Society of Animal Productior	
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the candidate analysed all data with assistance from Nicolas Lopez-Villalobos in developing the statistical models. The candidate wrote the first draft of the manuscript and undertook changes and corrections under guidance of supervisors	
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Date:	07/05/2019
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• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
the candidate analysed all data with assistance from Nicolas Lopez-Villalobos in developing the statistical models. The candidate wrote the first draft of the manuscript and undertook changes and corrections under guidance of supervisors	
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Name of Research Output and full reference:	
Handcock RC, Lopez-Villalobos N, McNaughton LR, Back PJ, Edwards GR, Hickson RE 2018. Live weight and growth of Holstein-Friesian, Jersey and crossbred dairy heifers in New Zealand. New Zealand Journal of Agricultural Research 62: 173-183	
In which Chapter is the Manuscript /Published work:	2
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	70%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
the candidate analysed all data with assistance from Nicolas Lopez-Villalobos in developing the statistical model. The candidate wrote the first draft of the manuscript and undertook changes and corrections under guidance of supervisors	
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Name/title of Primary Supervisor:	A/P Rebecca Hickson
Name of Research Output and full reference:	
Handcock RC, Lopez-Villalobos N, McNaughton LR, Back PJ, Edwards GR, Hickson RE. 2018. Dairy heifers: there is no such thing as too big. Proceedings of the Society of Dairy Cattle Veterinarians New Zealand Veterinary Association. 155-160.	
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Name of Research Output and full reference:	
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Handcock RC, Lopez-Villalobos N, McNaughton LR, Back PJ, Edwards GR, Hickson RE 2019. Positive relationships between body weight of dairy heifers and their first-lactation and accumulated three-parity lactation production. Journal of Dairy Science	
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Name of Research Output and full reference:	
Handcock RC, Jenkinson CMC, Laven R, McNaughton LR, Lopez-Villalobos N, Back PJ, Hickson RE 2019. Linear versus seasonal growth of dairy heifers decreased age at puberty but did not affect first lactation milk production. The New Zealand Journ	
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• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
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