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Association among pasture-level variables and grazing dairy cow responses to supplementary feeds

A thesis presented in partial fulfilment of the
requirements for the degree of

Master of Science
in
Animal Science

at Massey University, Manawatū,
New Zealand.

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2018

Abstract

The milk production response to additional feed (i.e., supplement) is dependent on the relative feed deficit (RFD) of the cow. We hypothesized that the relative feed deficit could be defined by post-grazing residual (PGR), with a greater PGR indicating less of a relative feed deficit. We undertook a computerized literature review, utilising key words associated with grazing systems and supplementary feed. Approximately 70 published manuscripts were reviewed. Only those that satisfied predetermined inclusion criteria were retained. A meta-analysis was undertaken across all the studies using random coefficient regression fitted as a mixed-model. In total, we collated data from 26 experiments and 90 treatments, wherein pasture-level variables, supplementary feed variables, and milk production were reported. Due to a lack of reporting of standard errors, two analyses were undertaken; one where responses were weighted against the reciprocal of the standard error of the mean, and one where they were not. On average, pasture DM intake declined (-0.28 kg/kg supplement DM; $P = 0.001$) and milk, fat, and protein increased ($P < 0.001$) 0.65 kg, 20g, and 30g/kg supplement DM, respectively. For every kg DM supplement consumed, PGR height and mass increased by 1.4 mm and 42 kg DM/ha. These results were similar in the non-weighted analysis. Associated with every 10 mm increase in PGR height in the control treatment, marginal milk response declined ($P < 0.05$) by 55 ± 21.6 g. The association between PGR height and pasture DMI at zero supplementary feed intake (i.e., unsupplemented group in experiment) on the PGR and pasture DMI responses to supplementary feed, were however, inconsistent in the weighted and non-weighted analysis. These results will enable farmers to use the change in PGR when feeding supplements, to estimate likely marginal milk production response to supplementary feeds. These results are associations only and need to be tested in controlled, interventionist, experiments. Due the number of variables affecting MR, we cannot conclude that anything is causative.

Acknowledgments

Firstly I must thank DairyNZ for providing the opportunity and financial support that allowed me to undertake this project. To study in a supportive environment, surrounded by the scientists who authored many of the works that I cited in this thesis, and who were always willing to answer questions, has been invaluable.

I would like to express my sincere gratitude to my supervisor Dr. John Roche for the continuous support and patience. Each meeting left me feeling motivated. Without John as my supervisor I would never have made it to China and still managed to get this thesis to the finish line. It has been a privilege to work beside him. I could not imagine having a better advisor, mentor and friend. Thank you for your life advice, your dad jokes and for always replying to my emails at ridiculous hours of the night.

My sincere thanks also go to Barbara Dow, who taught me everything I know about statistics. Without her support, it would not be possible to conduct this research. Thank you for always having time for me, and for keeping tabs on my progress. I don't know what direction this project would have taken had you not been there to help me.

Special thanks must also go to Dr. Danny Donaghy who timelessly read and re-read my literature review, and explained the intricacies of grazing management to me. Thanks also to my family and to my friends; Holly, Louise and Charlotte, for their understanding and encouragement as they too worked on their Masterate and PhD theses.

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List of Abbreviations

BW	Body weight
CSR	Comparative stocking rate
CNCPS	Cornell Net Carbohydrate and Protein System
DE	Digestible energy
DM	Dry matter
DMI	Dry matter intake
FCM	Fat corrected milk
GDP	Gross domestic product
ME	Metabolisable energy
MS	Milksolids
MR	Marginal response
NDF	Neutral detergent fibre
NSC	Non-structural carbohydrates
NZ	New Zealand
PA	Pasture allowance
PGR	Post grazing residual
RFD	Relative feed deficit
SbR	Substitution rate
SOL	Stage of lactation
SR	Stocking rate
TMR	Total mixed ration
VFA	Volatile fatty acids
WSC	Water soluble carbohydrates

Chapter 1 General Introduction

The international demand for milk, and protein in general, has steadily increased over the past 50 years, driven by the income growth of 'middle-class' populations in previously-designated developing countries (e.g., China and India; Wattiaux, 2017). New Zealand (NZ) is the world's largest milk exporter and, as the country's largest goods export sector, dairy is a fundamental component of NZ's trading economy. It contributes 3.5% ($7.8 billion) directly to NZ's GDP, but its responsibility for 30% of NZ's net export earnings results in a considerable secondary influence on national GDP (Ballingall & Pambudi, 2017).

There is considerable diversity in dairy systems throughout the world. In NZ, and in other areas of the world where climatic conditions permit, dairy cows derive most of the nutrients they require from grazing pastures. The operation of pasture-based systems, is, in many ways, a stark contrast to the systems that dominate the dairy industries of North America and Europe, which are predominantly characterised by intensive feeding in housed accommodation, and aim to maximize milk production per cow through the feeding of a formulated total mixed ration (TMR; Knaus, 2016). Throughout the world, however, dairy systems operate at any point along the spectrum between these extremes; for example, cows may graze pasture for part of the year and be housed for the remainder, or pasture can make up a portion of their diet, with the remainder from imported feeds (i.e., supplementary feeds; Wattiaux, 2017).

The use of supplementary feeds on pasture-based dairy farms increased during the 1970s and 1980s around the world (Leaver et al., 1968; Stockdale & Trigg, 1985) and, in particular, during the last two decades in New Zealand. In fact, they are now a central component of many pasture-based dairy farms, to the point, in some cases, where pasture is no longer the major feed type. Key drivers of this increase in supplement use include:

- As a means of mitigating feed deficit situations, as pastures cannot meet animal feed requirements if growing slowly or not at all due to drought or flood;
- A desire by farmers to feed cows 'better' or to produce milk to the genetic potential of cows;
- A belief that through greater milk production, fixed costs can be diluted;

- To allow increased stocking rates to improve pasture harvest. This has been fuelled by an understanding by farmers that an improvement in productivity and profitability requires the harvest of as much pasture *in situ* as possible. The higher stocking rates required to consume more pasture at peak periods of supply, have resulted in periods with larger feed deficits. Supplementary feeds have been considered the solution to bridge these deficits;
- Milk companies who want to flatten supply curves to optimise their processing capacity, offer incentives for milk production during 'off-peak' times. This has resulted in increased non-seasonal milk production, where pasture supply alone does not match cow demand, and supplements are used to fill the gap.

The NZ dairy industry, once renowned for being a world leader in low-cost milk production, has slipped from this position (Figure 1.1).

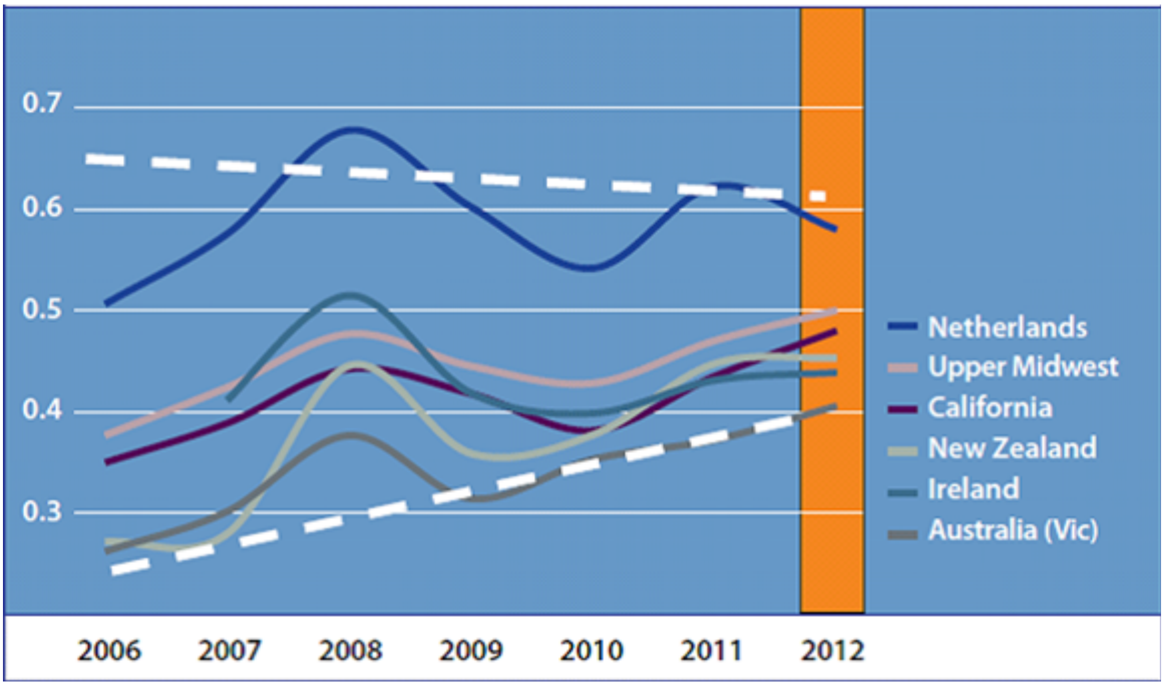

Figure 1.1 Farmgate milk production costs in selected countries 2006-2012.USD/litre (O'Mahony, 2014).

The decline in cost-competitiveness of the NZ dairy industry can be attributed mainly to the increasing costs of inputs, with purchased supplements being a key contributor to this (Figure 1.2; DairyNZ, 2017).

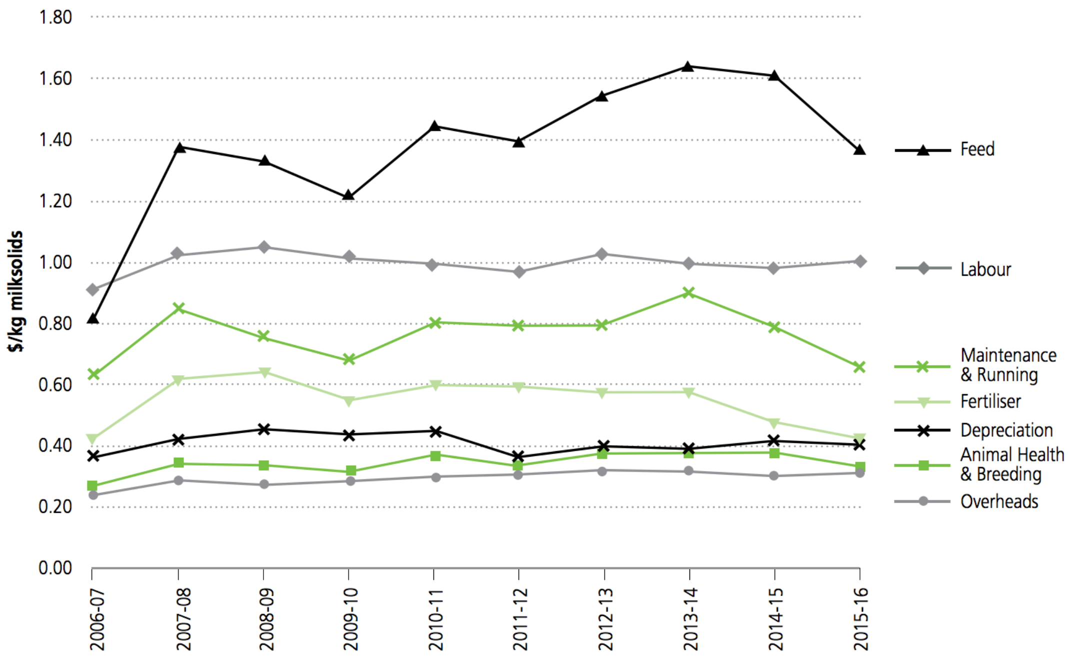

Figure 1.2: Operating expenses $ per kilogram of milksolids (DairyNZ, 2017).

With a small domestic population, NZ is an export-oriented country and the dairy industry is exposed to the international market for both milk price and many input prices. The volatile nature of both milk and feed prices has been more pronounced in recent times than previously (Hemme, 2017). The dairy farm that incorporates purchased supplements into its system is, therefore, exposed, to a greater degree, to the whims of international markets than a grazing system that doesn't purchase imported supplements, which only needs to cope with milk price volatility. This exposure escalates as the proportion of purchased supplements fed increases. However, these systems also have the advantage of capturing greater value from milk sales when milk prices are high, particularly when supplementary feed prices can be controlled. Profitable supplement use is driven by many factors, but primarily;

- Supplement price;
- Milk price; and
- Response to supplement.

While supplement price and milk price are beyond the farmer's control, the response to supplement can, to a large extent, be influenced by management. Understanding the expected milk production responses of cows to supplementary feeds is important for the economic assessment (cost/benefit) of feeding that supplement.

The marginal milk production response (MR) to a supplementary feed, is the extra milk, of a particular composition, produced from the most recent increment of supplement consumed (Heard et al., 2017). In the research undertaken, there is considerable variation in the responses to supplementary feeds in pasture-based dairy systems. This variation stems from many complex factors that interact to affect the substitution of supplementary feeds for pasture. Penno (2002) hypothesised that the most important factor determining the cows' response to supplementary feeds is the level of hunger the cow is experiencing prior to consuming the supplementary feed. It has since been proposed that pasture-level variables (e.g., post-grazing residual height or mass) may be used to estimate the extent of this hunger and thus to estimate the MR to supplementary feeds. This thesis sets out to investigate this.

Chapter 2 Literature Review

2.1 Introduction

New Zealand dairy systems are characterised by a reliance on pasture to feed livestock. The biggest advantage of the pasture-based system is the low cost of production, a consequence of reduced labour, capital and machinery costs, as cows harvest their own feed and live outdoors. Indeed, under most circumstances, pastures are the cheapest feed source (Chapman et al., 2008; Savage & Lewis, 2005) and farm systems with a higher proportion of pasture are able to achieve lower costs of production (Figure 2.1; Peyraud & Delaby, 2001; Dillon et al., 2005).

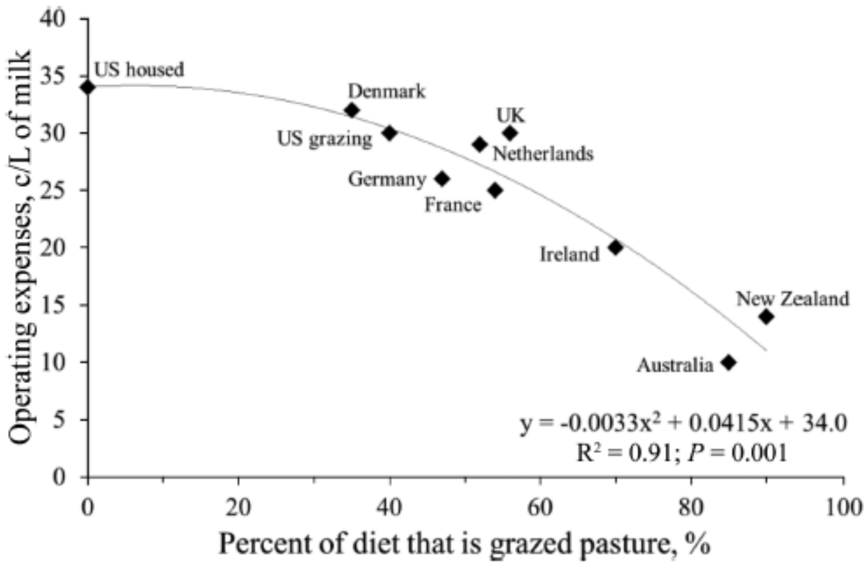

Figure 2.1: The association between the percentage of the cow's annual diet that is grazed pasture and the cost of milk production (Dillon et al., 2005).

The main disadvantage of pasture-based systems is the heavy reliance on a moderate climate and reliable rainfall pattern, which are required to maintain pasture growth rates. Because of this, lactation length is shorter than average (generally <220-240 days, unless supplementary feeds are used; Holmes et al., 2002). Furthermore, the management of a pasture-based dairy farm is complicated by the need to coordinate the herds' energy demand with a fluctuating pasture supply. Even under ideal conditions, periods of mismatch between pasture supply and cow nutrient demand are inevitable, and milk production per cow is negatively affected. Purchased supplementary feeds are increasingly used to facilitate the management of pasture-based dairy farms and to achieve greater yields of milk fat and milk protein (Bargo et al., 2003) per cow and per hectare.

The provision of supplementary feeds to grazing dairy cows influences the way they graze and, thus, affects pasture utilisation. The change in pasture utilisation that occurs when supplementary feeds are offered, is influenced by the ability of the pasture to fulfil the herds' feed requirements prior to the provision of the supplement (Penno, 2002). This is because the substitution of the supplementary feed for pasture is greater when a cow is less hungry (Stockdale, 2000; Roche & White, 2012). To maximise both pasture utilisation and the MR to supplements, the allowance of supplementary feeds offered, should, therefore, be determined and adjusted based on how hungry a cow is (Roche & White, 2012).

For supplements to result in positive financial returns, the MR to the supplement provided must be large enough to cover the cost of the supplement as well as the additional costs associated with feeding it. For example, harvesting more milk and/or carrying more cows results in costs additional to the cost of the feed facilitating the system change.

The aim of this review is to collate and interpret research that has investigated the supplementary feeding of dairy cows in pasture-based systems. This will facilitate an understanding of the variation that exists in reported responses to supplements. It is important to understand this response to ensure that the maximum MR is obtained from feeding the supplement.

2.2 Pasture-based systems

Grazed pastures are a primary dietary component on 80% of the world's agriculturally productive land (Boval & Dixon, 2012). In New Zealand and in other countries with temperate climates and sufficient rainfall, grazed pastures provide the main source of nutrients to dairy cows. In such systems, a key factor in maximising the efficiency of utilising pasture, is the ability to synchronise herd nutrient requirements with pasture supply (Roche et al., 2017).

The main advantages of the pasture-based system are:

- Pasture is a nutritious, safe feed for dairy cattle. Provided it is managed appropriately (i.e. not over-fertilised, or grazed too frequently), it shouldn't cause any health issues (Roche, 2017);
- When appropriately managed, pasture can maintain high quality year-round (Roche et al., 2009);
- It facilitates a low cost of milk production, a consequence of reduced labour, capital and machinery costs, as cows harvest their own food, and live outdoors (Dillon et al., 2005);
- Because cows aren't restrained by sheds or tethering, they are more free and, so, are able to exhibit more natural behaviours (i.e., can graze and socialise). This has positive real and perceived animal welfare implications (Arnott et al., 2017; Roche et al., 2017);
- There is a growing understanding among consumers that milk from the pasture-fed cow is a 'healthier' and more desirable product than the milk produced from grain (or concentrate)-fed animals (Roche et al., 2017); and
- In times of excess supply, pasture can be conserved as silage or hay (Holmes et al., 2002).

The main disadvantages of pasture-based systems are:

- The seasonality of pasture growth profiles. This can result in gaps in supply and a short lactation length compared with TMR systems (Holmes et al., 2002);
- The feeding value of pasture changes throughout the year. Seasonal and spatial variation in temperature, moisture, light concentrations and soil nutrition result

in herbage that varies in minerals, fibre, protein and energy (Figure 2.5; Roche et al., 2009); and

- The requirement for calving and mating dates to occur at certain times. The aim is to synchronise the majority of calving prior to the peak in pasture growth to coordinate the feed supply and demand curves. To achieve this, the cow must become pregnant within approximately 80 days of calving (Figure 2.2; Roche et al., 2017b).

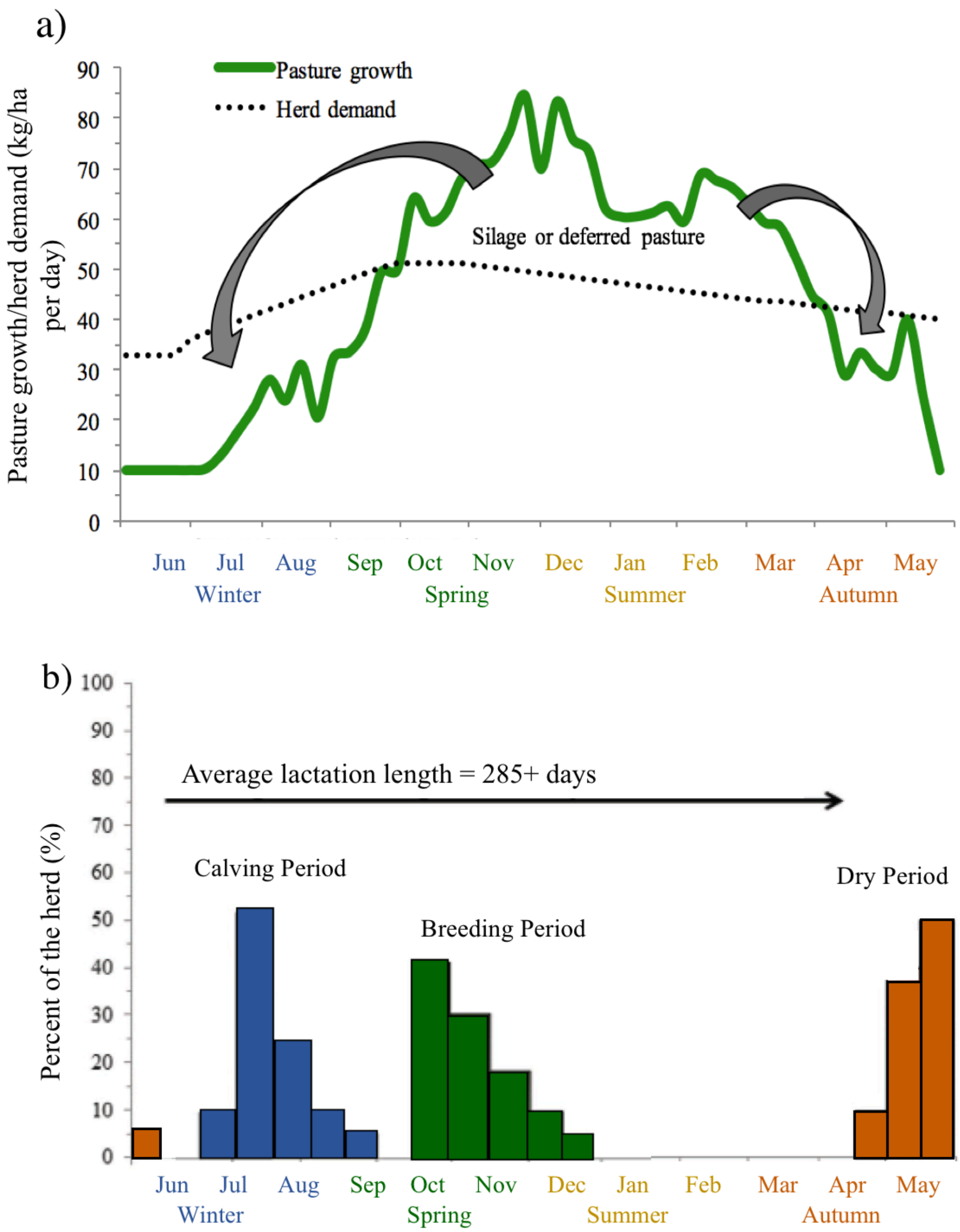

Figure 2.2. a) Temporal pattern of daily pasture supply and herd demand and b) Proportion of the herd at different stages of SOL. Adapted from (Roche et al. 2017)

In pasture-based systems, the ability to balance or 'match' feed demand and supply is closely linked to the overall quantity of pasture harvested per hectare, and the subsequent utilisation of that pasture (Kellaway & Harrington, 2003; Dillon et al., 2005).

Key influences of feed demand include:

- Stocking rate (SR; number of cows per unit of land);
- Start date of calving; and,
- Calving spread.

Key influences of feed (pasture) supply are:

- Pasture cover at calving;
- Pasture growth rate; and
- Grazing management.

The following section will consider the key drivers of feed demand and supply.

2.3 Feed demand drivers

2.3.1 Stocking rate

An appropriate SR has been recognised as the most important management factor in determining the feed demand on farm for many decades if not centuries, and the ability of pasture to satisfy demand. In fact, it was over 50 years ago that McMeekan stated that "*No more powerful force exists for good or evil than the control of stocking rate in grassland farming. Properly understood and used, it can influence productive efficiency for good more than any other single controllable factor*." (McMeekan, 1960).

Stocking rate is commonly expressed as the number of cows per land unit (i.e., hectare or acre). This expression is simplistic, and does not allow for an accurate comparison between dairy farms for the following reasons:

- Cow maintenance feed requirements are a function of cow size;
- Pasture growth is dependent on soil type, climate, latitude, and management; thus, the ability of a unit of land to produce pasture is not consistent, even within farms;
- A dairy business may carry several classes of stock, other than the milking herd, that will also consume pasture; and

- A farm that utilises imported feeds needs to have a higher SR than one that is entirely self-sufficient, to ensure high MR to the supplement (Macdonald et al., 2017). Thus the use of SR alone does not reflect the ability of a unit of land to satisfy the feed demand of the herd. All feed sources need to be included.

Macdonald et al., (2008) proposed an alternative measure, which they called comparative stocking rate (CSR). Expressed as kilograms of cow bodyweight (BW) per tonne of total feed available, CSR accounts for both production potential of the farm and the cow, any supplementary feeds imported, other classes of livestock, and is a more accurate measure of effective SR than is cows/ha.

Macdonald et al. (2008) reported that optimum CSR was 78 kg BW/t of feed dry matter (DM) in a system not importing supplements, and closer to 95 kg BW/t of feed DM when supplements were part of the system. Where the CSR is low, there will likely be sufficient pasture to feed the herd throughout the year, but there will be periods when pasture must be conserved as pasture silage or hay, or through deferred grazing to prevent it from being wasted (i.e. utilisation will decline). This is most likely to occur in the springtime, when pasture growth rates are high. In a closed system (i.e. where supplements are not purchased), the limitations imposed by the seasonal distribution of pasture may be overcome by the feeding of this conserved pasture, during times of deficit (Figure 2.3).

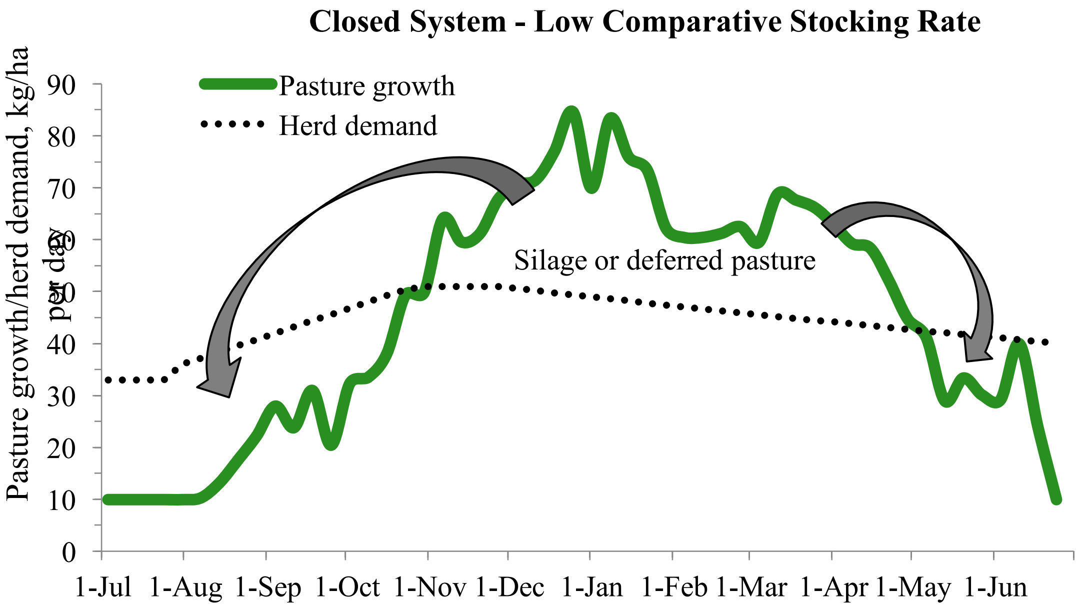

Figure 2.3: Seasonal closed system (i.e. where supplements are not purchased) and where pasture is conserved during periods of surplus and fed during times of deficit. Adapted from Figure 2.2a (Roche et al. 2017).

Conversely, when the CSR is high, the feed demand is higher and pasture allowance per cow is low. Cows will likely consume less, and consequently, produce less milk. High SR's are therefore restricted to an open system (i.e. where supplements are purchased), and the limitation imposed by the seasonal distribution of pasture is overcome by the feeding of supplementary feeds (Figure 2.4).

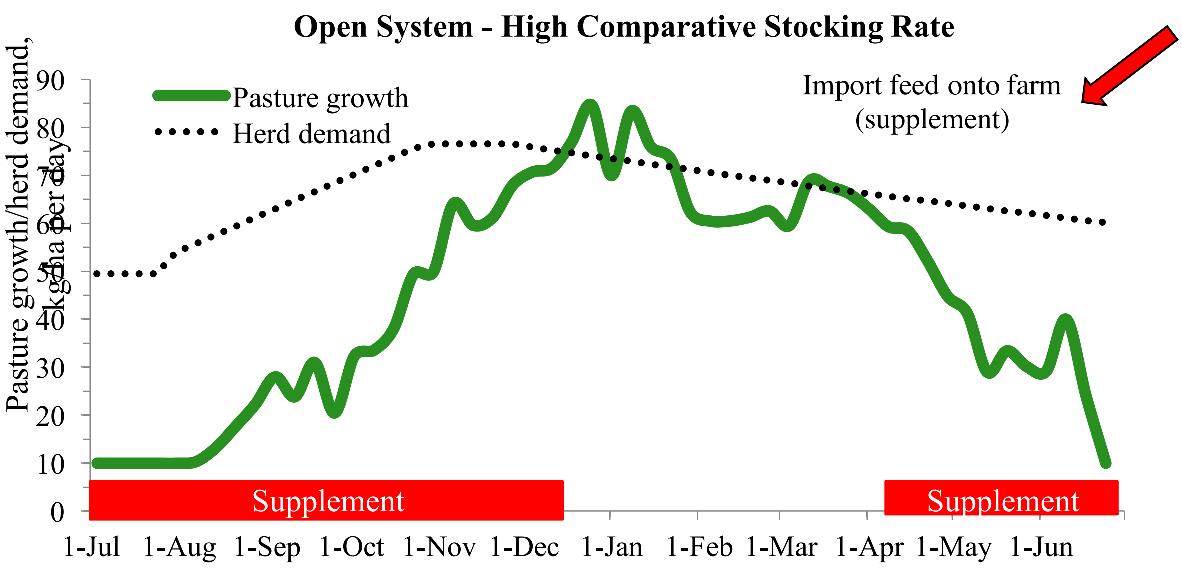

Figure 2.4: Seasonal 'open' dairy farming system (i.e. where supplements are purchased). The herd demand exceeds the supply of pasture for most of the year, and therefore supplements must be fed to fill the deficit. Adapted from Figure 2.2a (Roche et al. 2017).

An optimum SR is crucial in all pasture-based systems to ensure high utilisation of pasture, with minimal amounts of pasture conservation (Kolver, 2003). In addition to SR, the planned start of calving and the calving spread are also important influencers of the ability of the pasture supply to satisfy herd feed demand.

2.3.2 Calving date

The demand for feed by a lactating cow is greater than that of a non-lactating cow (i.e. a cow that is in preparation for calving, commonly referred to as a 'dry' cow). Thus, both the onset of lactation following calving (i.e. the calving date), and the cessation of lactation through drying-off the herd, have a sudden and substantial impact on the feed demand.

Varying climatic conditions and pasture growth profiles mean that different regions have different recommended 'planned start of calving' dates. The decision surrounding the determination of this date is driven by the need to coordinate the period when cows have the highest energy demand (10-12 weeks post-calving) with the peak supply of pasture, which occurs in spring. Conversely, it aims to ensure that the minimum feed demand of the herd (that occurs when the herd is dry), coincides with the period of slowest pasture growth and lowest feed supply (in the winter; Figure 2.2a).

On average, calving should begin approximately 60 days before balance date (i.e. when pasture supply is equal to feed demand; (Holmes, 1995; Roche et al., 2017)

2.3.3 Calving spread

While calving date refers to the day when calving begins, calving spread is the time lapsed from the beginning to the end of the seasonal calving period. A compact calving period (i.e. short spread), provided calving start date is appropriate, will help to synchronise the feed demand of the herd with the growth rates of pasture. The goal is for 50% of the herd to calve within 2 weeks from the start date, and the entire herd to have calved within a 10-week period (Roche et al., 2017). However, a compact calving period that begins earlier than this increases the likelihood that feed demand will exceed pasture supply.

To attain this compact calving period, maintaining a 365-day inter-calving interval is crucial. Therefore, cows that fail to conceive during the short breeding period (70-84 days; Roche et al., 2017a) are culled from the herd. Consequently, on average, cows in grazing systems have shorter lactation lengths than those that are housed and calve all year-round.

Both calving date and calving spread must be appropriate to ensure that feed supply can meet animal demand in a pasture-based system. The attainment of one of these in the absence of the other, will likely result in a mismatch between feed supply and demand and cause inefficiencies in the system.

2.4 Drivers of feed supply

2.4.1 Average pasture mass at calving

Average pasture mass/ha at calving, which is often referred to as 'pasture cover' by farmers, is the average mass of pasture/ha on the farm when the planned start of calving begins.

Because the beginning of calving is planned to occur 60 days prior to when pasture growth rates in spring are equal to the herd's demand (referred to as 'balance date'), a temporary pasture deficit situation during late winter is common. Though this deficit can normally be managed through the feeding of pasture accumulated in autumn (through long grazing rotations that allow the pasture mass to accumulate) and previously-conserved pasture (silage), the average pasture cover at calving has a large effect on the ability of pasture to meet the herd's feed demand.

Pasture cover at calving should be sufficient to allow newly-calved cows to be adequately fed. At the same time, however, if average pasture cover is too high at calving, then pasture quality will decline before the subsequent grazing, and milk production will decline when the cows consume that pasture (Lee et al., 2008b). Conversely, if average pasture cover at calving is too low, the herd may be underfed. Two key determinants of pasture cover at calving are pasture growth rates and grazing management.

2.4.2 Pasture growth rates

Pasture growth rates are a key determinant of the feed supply in a pasture-based system. As discussed in section 3.1, day length, temperature and moisture drive seasonal growth rates. Thus, in the spring, pasture growth rates peak, and often result in surplus pasture supply, while in the winter and summer, pasture growth rates slow down, commonly resulting in feed deficits in winter. Management policies such as SR or calving date, which have a major bearing on total feed demand, are selected to align the feed supply and demand curves, and are based on expected pasture growth rates. However, climate variability drives year-to-year variability (inter-annual variation) in pasture growth rates, making the accurate alignment of feed supply and demand curves difficult in practice. This inter-annual variation in pasture growth is considered one of the major sources of inefficiency in temperate, pasture-based dairy systems (Gentilli, 1971).

Sheath and Clark (1996) investigated the effects of adjusting or maintaining the grazing rotation length in response to pasture growth rates being 50% lower than average, in early spring (August/September) for a North Island, NZ, dairy herd with a planned start of calving on the 20th July. When the grazing rotation length used in an average pasture growth rate year was maintained (i.e. the area offered to graze remained constant) through the period of growth restriction, much less pasture mass accumulated (1220 kg DM/ha versus 2170 kg DM/ha) than when the rotation was lengthened (less area offered per day), to maintain an average farm pasture cover of at least 1700 kg DM. Not adjusting the rotation length to suit pasture growth rates therefore had a significant effect on the feed supply and resulted in 42% less milksolids (MS) production/ha for the whole lactation. This example not only demonstrates the importance of pasture growth rates on the feed supply, but also grazing management to ensure the maximum pasture harvest possible under climate conditions outside the farmer's control.

2.4.3 Grazing management

The rate of regrowth of pasture following defoliation conforms to a sigmoid or S-shaped curve (Brougham, 1955), which is underpinned by the replenishment of energy reserves (Weinmann, 1948). Grazing management affects pasture growth supply through its effect on this sigmoid growth curve. For example, rotation length is a key driver of pasture growth, through allowing (or not) sufficient time for pasture plants to recover their reserves and proceed along the sigmoid curve. Post-grazing residual (PGR; determined by grazing intensity) is a key driver of pasture growth through setting the 'starting point' for the sigmoid curve as well as determining the shape of the curve; e.g. higher PGR's result in a steeper curve but canopy closure occurs sooner.

Grazing management, pasture growth rates and pasture cover are interrelated, in that grazing management determines pasture growth rates, which in turn underpin average pasture cover at calving.

2.4.4 Summary

The strategic decision-making around SR, calving date, and pasture cover at calving is important in coordinating feed demand and pasture supply curves. These management policies are all underpinned by pasture growth rates which vary annually and which are difficult to predict. Pastoral dairy farming is a balancing act between pasture and animal factors, and often what maximises milk production may not maximise farm efficiency or profit. A key difference between TMR and pasture-based systems is that the focus for TMR cows is per cow performance, because overhead capital costs are associated with each cow, whereas the focus for pasture-based cows is cow performance per unit of land, because land represents the majority of capital employed. After SR, calving date and pasture mass at calving, grazing management is the key to maximising cow performance per land unit.

2.5 Grazing management principles

In a pasture-based system, profitability is closely linked to the utilisation of pasture (Kellaway & Harrington, 2003; Dillon et al., 2005). The achievement of high pasture utilisation requires a focus not only on maximising the quality and quantity of pasture grown, but also on the pasture consumed per hectare, over the entire season. This requires careful grazing management.

When both grazing management and SR are optimised, pasture growth rates correspond to the rate of pasture consumption, so that:

- The feed requirements of the herd are adequately satisfied throughout the year;
- Pasture is eaten by the cows at the correct stage of growth, reducing pasture wastage;
- The regrowth potential of the plants in the pasture is not compromised; and
- The nutritive value of the pasture remains high.

Grazing management is complicated by changes in both quality and quantity of pastures at different times of the year (Roche et al., 2009). When not correctly managed, wastage occurs, which invariably makes pasture a more expensive feed source. Although a number of factors combine to alter pasture yield and quality, there are principles of pasture management that can be generically applied to optimise the management of pasture.

2.5.1 Quality

Pasture quality varies throughout the year and is largely influenced by the type of growth that is occurring, as well as by climate. Cow production in a pastoral-based dairy system, is partly the result of the quantity and nutritive value of the pasture consumed, which is summarised by metabolisable energy (ME) yield (Lee et al., 2008). A key aspect of pasture quality is DM digestibility, used to calculate ME yield. Hereafter, pasture quality will refer to pasture digestibility. For most of the year, the plant is in a vegetative state, with a high proportion of leaf and a low proportion of stem present in the sward. However, in spring, the plant undergoes reproductive growth, which results in stem elongation and production of a flowering seed head. Reproductive growth is associated with an increase in fibre, and a concomitant decrease in digestibility and ME, in the sward. In New Zealand, the major period of reproduction in pastures is late spring (October and November) (Figure 2.5; Holmes et al., 2002).

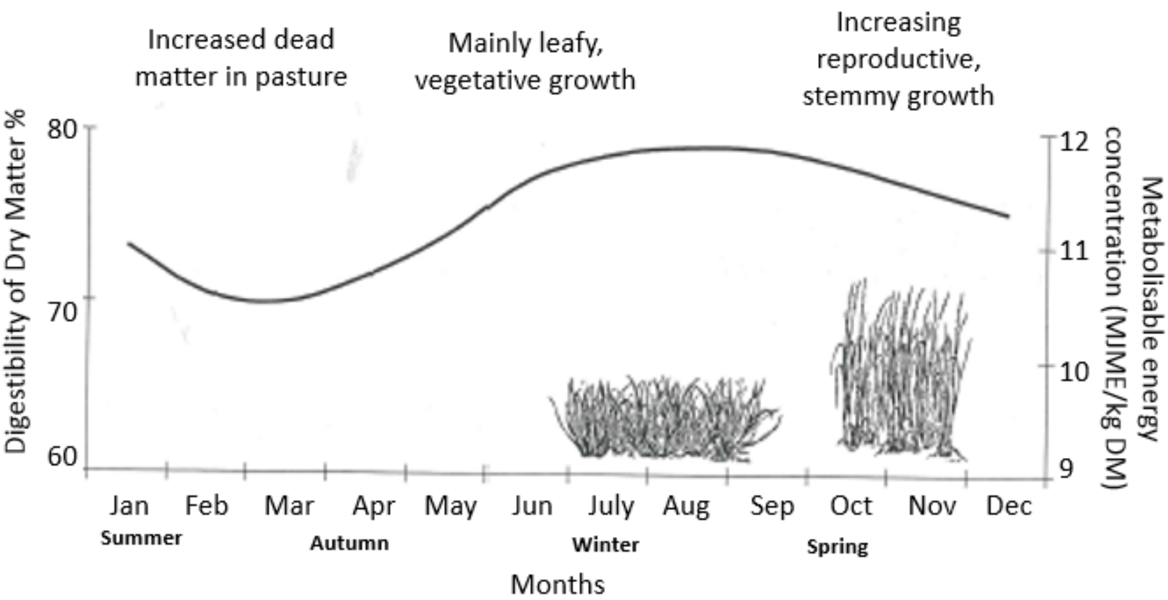

Figure 2.5: Seasonal changes in the nutritive value of well-managed ryegrass/clover pastures (Holmes et al., 2002)

In addition to reproductive growth occurring, the spring period is also associated with faster growth rates and increasing temperatures, both of which result in higher fibre levels in plants. Combined, these 3 factors contribute to the opportunity for increased PGR's (either due to over-allocation of pasture to stock as growth rates fluctuate quickly, or greater rejection of more fibrous pasture by grazing animals). Grazing management in spring is important to ensure that the timing and intensity of grazing minimises the production of stem in the pastures to maintain quality. The most important facets of grazing management to optimise pasture quality are grazing interval (i.e. rotation length; the time elapsed between subsequent grazing events) and grazing intensity (i.e. PGR; how much remains after grazing). Grazing interval and intensity control the extent of reproductive growth, tillering, and fibre production, therefore, grazing management can markedly influence the overall productivity of a pasture.

2.5.2 Grazing interval

The resilience of a grazing system is dependent on the ability of the pasture plant to survive defoliation and, then, propagate in a timely manner. The frequency by which a pasture is grazed (i.e., grazing interval), through its effect on the time required for the pasture to recover, influences total pasture harvest and total pasture utilisation. The basic principle by which an effective grazing interval is determined, is that the lifespan of a perennial ryegrass leaf equates to the period taken for three leaves to grow per tiller (Fulkerson & Donaghy, 2001).

Leaf stage determines the appropriate grazing interval from a plant physiology perspective. Perennial ryegrass is referred to as a '3-leaf' plant, as each tiller can sustain about three live leaves at once (Davies, 1960). As a fourth new leaf emerges, the oldest leaf dies and is wasted (Figure 2.6).

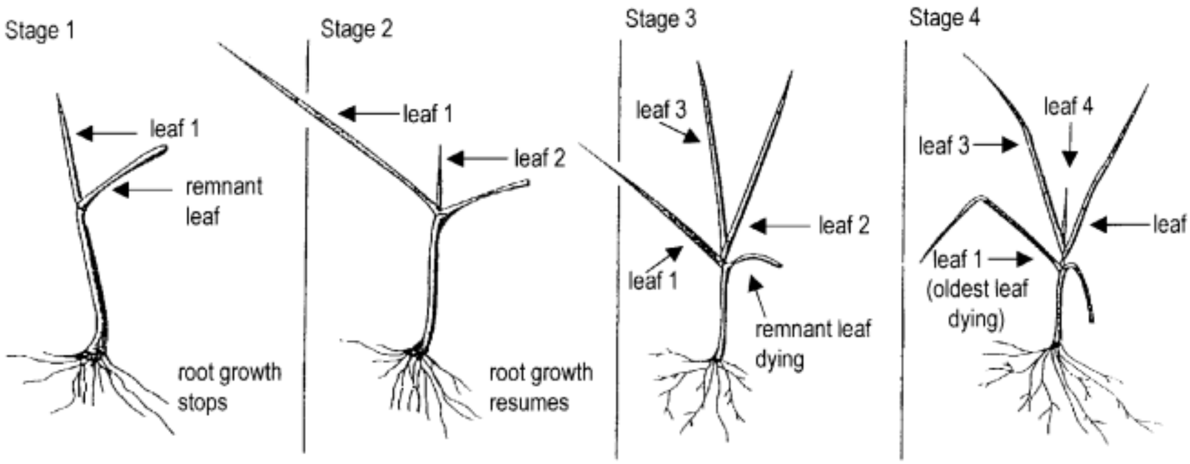

Figure 2.6: Regrowth of a ryegrass tiller following defoliation (Donaghy 1998).

Following a grazing bout, where pasture utilisation is high, the remaining leaf on a perennial ryegrass plant is scarce. Consequently, its photosynthetic ability is impaired (Lee et al., 2010). To survive and then propagate, the plant must rely on its reserves of non-structural carbohydrates (NSC), which are mainly stored in the lower 40 mm of the tiller base, or 'stubble' (Lee et al., 2008a). Non-structural carbohydrates comprise water soluble carbohydrates (WSC) and starch and are produced by photosynthesis. They are the energy source that is used to regrow the first leaf that will rebuild the photosynthetic capacity of the plant.

It is only when the energy requirements for growth and respiration have been met that the plant can partition NSC to storage reserves, and this is where leaf stage becomes important. At the 2-leaf stage of regrowth, NSC reserves are generally adequate for the plant to tolerate being grazed again, without compromising its regrowth potential (Donaghy & Fulkerson, 1998; Figure 2.7).

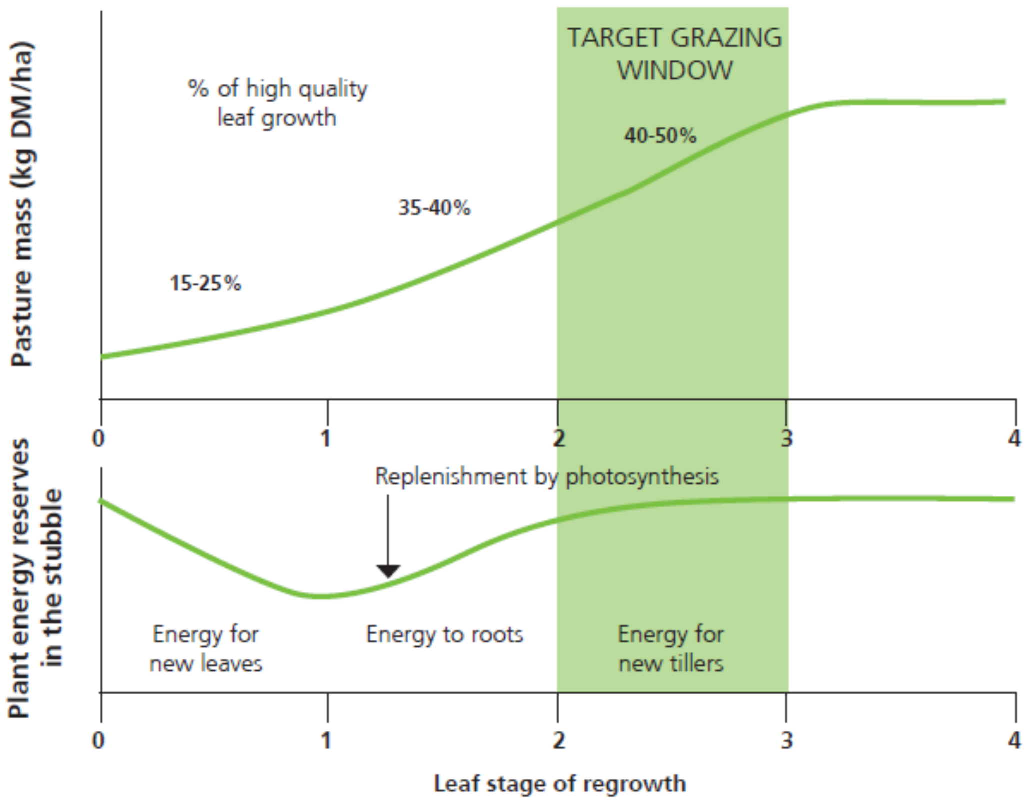

Figure 2.7: Change in pasture mass and plant energy reserves during the re-growth cycle of perennial ryegrass (McCarthy et al., 2015).

Frequent grazing (< 2-leaf stage for ryegrass) prevents plants from accumulating sufficient NSC reserves (Lee et al., 2007; Lee et al., 2010). Consequently, the regrowth potential of the plant is compromised, relative to less-frequently grazed pasture. Donaghy and Fulkerson (1997) highlighted the effect of grazing frequency on ryegrass plant regrowth by demonstrating that plants subject to frequent defoliation (grazed at 1 leaf/tiller for 3 successive grazing bouts) accumulated significantly less pasture mass than those grazed less-frequently (at 3 leaves/tiller for 3 successive grazing events). Interestingly, the pasture mass of plants grazed at 2 leaves/tiller for the same time period, was in line with those grazed less frequently (3 leaves/tiller) by 36 days post-defoliation event. This indicates that, provided an adequate regrowth period is enabled, the initially lower NSC reserves from grazing more frequently, may be compensated for (Figure 2.8).

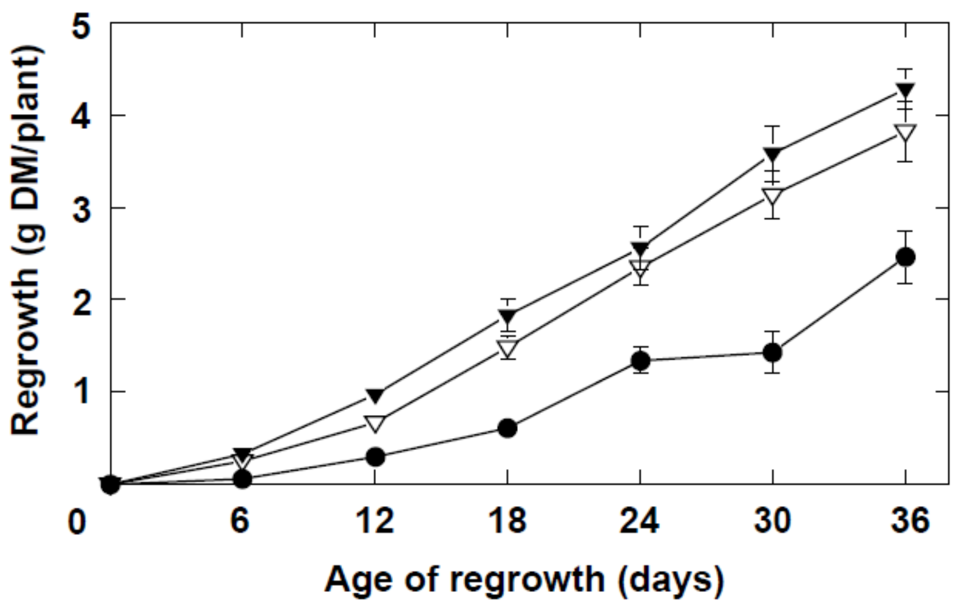

Figure 2.8: Regrowth to 3-leaf stage (36 days) when plants were previously defoliated once at 3 leaves (▼), once at 1 leaf and once at 2 leaf (▽) or 3 times at 1 leaf (●) per tiller (Donaghy and Fulkerson 1997)

The minimum sustainable grazing interval, therefore, is considered the 2-leaf stage of regrowth. At this stage, NSC reserves have been sufficiently replenished for the plant to cope with being re-grazed (Lee et al., 2010). The 3-3.5 leaf stage is considered the maximum grazing interval. The consequences of grazing beyond this maximum grazing interval include:

- increased wastage, as the number of dead leaves increase;

- increased shading of other tillers and clover stolons, depressing their growth and eventually leading to their death; and
- a decrease in the nutritive value of the pasture, as neutral detergent fibre (NDF) increases and NDF digestibility and ME levels decline (Lee et al., 2008a; Lee et al., 2009).

Frequent grazing has, however, been reported to encourage tillering and reduce stem development, as the grass starts to grow reproductively in the spring (Chamberlain & Wilkinson, 1996). Pembleton et al., (2017) and Rawnsley et al., (2014) demonstrated that the 'ideal' or 'optimum' grazing frequency is location and season specific; where and when pasture growth rates are faster (in those studies in excess of 60 kg DM/ha/day), a faster grazing interval (grazing at the 2-leaf stage) was required to encourage tillering and maintain plant density and quality when compared with times that growth rates were slower and a slower interval (grazing at the 3-leaf stage) was deemed optimal.

By using leaf regrowth stage as an indicator to determine grazing interval, not only has the net accumulation of plant DM been demonstrated to increase, but also, the persistence and quality of the plant improves (Fulkerson & Donaghy, 2001; Pembleton et al., 2017). The principle of leaf stage is that there's a 'window' of opportunity between 2 and 3.5 leaves, when plants have recovered from grazing (2-leaf stage) and death, decay and a decrease in quality are yet to occur (3-leaf stage).

2.5.3 Grazing intensity

Grazing intensity is how severely (i.e. how close to the ground) a pasture is grazed (Holmes & Roche, 2007). Through its effect on the quantity of NSC stored, it affects the regrowth potential of a plant, and thus influences overall pasture harvest and utilisation.

Non-structural carbohydrates are located throughout the plant, with the highest concentrations (main storage site) in the plant stubble (especially the bottom 40 mm), then the leaf, with the smallest NSC concentration in the roots (Fulkerson & Donaghy, 2001). A severe grazing, therefore, especially to a PGR of less than 40 mm, removes a larger proportion of stored NSC and reduces subsequent storage capacity to a greater extent than a less severe (lax) grazing bout (Lee et al., 2009).

The height of the pasture post-grazing (i.e. PGR height) is now accepted as the most practical way to evaluate grazing intensity (Rawnsley et al., 2014; Roche et al., 2017). However, the literature is inconsistent, as to the ideal PGR height to achieve the correct balance between cow production and pasture utilisation (Ganche et al., 2013); both of which are key determinants of farm efficiency in a dairy grazing system. McEvoy et al., (2008) recommended a PGR height of 40 mm during spring and in support of this, Lee et al (2008) reported that when cows were offered a similar allowance, the same milk production could be achieved when they were consistently grazing to 40 mm PGR height as to 50 and 60 mm PGR. Ganche et al., (2013) reported that a PGR of 35 mm in spring would result in simultaneous high milk production and pasture utilisation. These experiments support current recommendations that a PGR height of 35-40 mm will result in the maximisation of pasture growth and utilisation (Roche, 2017).

2.5.4 Grazing management and pasture yield

Grazing systems research undertaken both in New Zealand and abroad, has compared the influence of lax and severe grazing events on overall pasture production. It has been demonstrated that lax grazing in winter and spring increases the amount of senescent material and stem in the pasture, lowering the nutritive value of the pasture for subsequent grazing's (Korte et al., 1984; Michell & Fulkerson, 1987; Holmes et al., 1992; Hoogendorn & Holmes, 1992; Stakelum & Dillon, 2007). In contrast, by maintaining a lower pasture mass, the leaf to stem ratio is increased (Hoogendoorn et al., 1992, Kennedy et al., 2007; Roca-Fernandez et al., 2011), the percentage of dead matter is decreased, percentage of clover is increased, and nutritive value is increased (Hoogendorn et al., 1988; Holmes et al.,1992).

2.5.5 Grazing management and milk production

Many studies (Le Du, 1979; Mayne et al., 1987; Wales et al., 1998) have reported that intensive grazing reduces milk production. However, the design of most of these experiments means that the effect of grazing intensity on milk production cannot be separated from the confounding effect of pasture allowance (PA). This prevents the conclusion that intensive grazing has a negative effect on milk production from being reliable.

In experiments where PA remained constant, and only grazing intensity differed, it was demonstrated that neither the yield of fat-corrected milk (FCM) nor milk components, were affected by grazing to a low sward height (Lee et al., 2008b). In fact, Holmes et al. (1992) observed an increase in daily milk production (22.3 kg/cow vs 19.9 kg/cow) when grazing paddocks that had been more intensely grazed in the prior grazing, and had a lower pre-grazing mass (2900 kg DM/ha vs 5100 kg DM/ha), while PA remained constant across treatments. These results were attributed to an improved quality (i.e. higher leaf to steam ratio and dry matter digestibility and thus nutritive value) of the pasture consumed. This conclusion is supported by Kolver (2003), who demonstrated that the proportion of lignin in the diet affected predicted milk production; as the lignin content increase from 60 to 66 g/kg NDF, the predicted ME- and amino acid-allowable milk decreased by 0·3 and 0·4 kg/d respectively. A lower lignin content, increased predicted milk production as more NDF was digested.

Overall, the ideal PGR height is 35 to 40 mm, as most NSC is stored below this point (Ganche et al., 2013; Roche, 2017). In the range of 35 mm to 80 mm however, there is little effect on pasture DM yield (Roche et al., 2017).

2.5.6 Summary

It is important to note that grazing frequency and grazing interval are interconnected. Logically, a plant that has been defoliated more intensely, will require a longer relative period of recovery; and vice-versa in that lax defoliation requires a shorter period prior to re-defoliation, as canopy closure occurs in a shorter time span. In pasture-only systems, where there is no ability to feed supplements, interval ‘drives intensity’. For example, slowing the grazing interval means that grazing intensity increases (i.e. animal demand stays the same and, with less area offered because the rotation is slowed, animals graze closer to the ground than previously). Shortening the grazing interval, without dropping paddocks out for silage, means that PGR will increase, as cows won’t graze as close to the ground. Post-grazing residuals can, therefore, be used as an indicator of the relative feed demand (RFD) of the herd, as cows that are less hungry, will lower their intakes of pasture when offered supplementary feeds, and PGR’s will increase (Wales et al., 1998).

2.6 Pasture as a nutrient source for grazing dairy cows

Perennial ryegrass (*Lolium perenne* L.*)* and white clover (*Trifolium repens* L.*)* pastures are the most predominant in New Zealand dairy farming (Kemp et al., 2000). Annual DM yield differs with the varying environments in different regions as well as a result of management.

Pasture, like any feed source, is comprised of water and DM. The water content of the pasture is determined by many factors, including the weather, species composition, and stage of growth, with younger plants and plants earlier in the growth stage, having a higher water content than older plants. The DM component of pasture can be further separated into organic and inorganic material. The energy derived by the cow as it consumes pasture comes from the organic fraction, comprised of carbohydrates, lipids, proteins, nucleic acids, organic acids and vitamins (Figure 2.9).

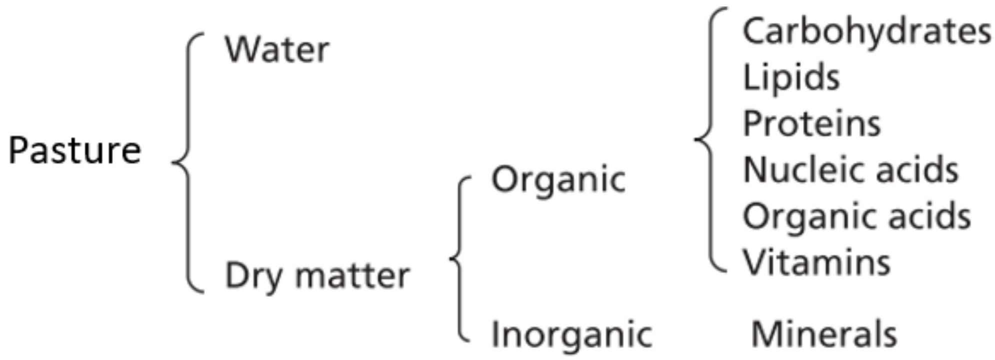

Figure 2.9: The main components of pasture (McDonald et al., 2011).

Numerous factors drive the nutrient requirements of cows, including milk yield and composition, requirements for maintenance and pregnancy, level of body tissue mobilisation or accretion and, to a certain degree, the quality of the diet (Kolver, 2003). These requirements were predicted by Kolver (2003) using the Cornell Net Carbohydrate and Protein System (CNPS; Table 2.1). The CNCPS is a model that predicts a cow's requirements for ME and protein, and the amount of these supplied by the diet.

Table 2.1: Nutrient requirement[1] and supply for cows of 550 or 650 kg live weight, producing 25 or 35 kg of milk. Adapted from (Kolver, 2003).

Live weight (kg)		550		650	
Milk production (kg/d)		25	35	25	35
Nutrient requirements					
Metabolisable energy (MJ/d)		207	229	216	260
Metabolisable protein (g/d)		1704	1947	1730	2222
Nutrient supply					
DM Intake:	kg/d	17.3	19.1	18	21.7
	g/kg live weight	31	35	30	33

[1]Predicted using the Cornell Net Carbohydrate and Protein System model. Assumes no liveweight gain or loss.

In assessments of the adequacy of a pasture-only diet to meet cow requirements, comparisons are frequently made with the TMR offered to cows in housed systems in North America and Europe. Although the diets are very different, with one made up of fresh forage harvested by the cow and the other nutritionally balanced for cow requirements with conserved forage (i.e. silage, hay, straw), cereal grains, and co-product feeds (i.e. waste from the human food, cosmetic and textile industries), from a nutritional point of view they are similar apart from the cow DM intake (DMI) and the primary source of the carbohydrate (i.e. structural vs storage carbohydrates). When supplements with high levels of storage carbohydrate (e.g. concentrates) comprise a considerable proportion of the diet, the level of total DMI that can be achieved is greater than on pasture-only diets (Kolver, 2003). This is because the higher DM content of concentrates mean that cows can consume more DM in a shorter time period, than when grazing pasture. As the result of an efficient synthesis of microbial protein coupled with the high protein content (> 220 g/kg DM) of pasture, the quantity and profile of amino acids available for absorption are rarely limiting factors for milk production, despite (or perhaps because of) the highly-degradable nature of pasture protein. Thus, for the majority of situations in temperate grazing systems, ME intake, as a result of DMI constraints, is the primary nutritional component limiting milk production (Roche, 2017).

This section will discuss DMI and carbohydrate type in pasture-only versus TMR diets, and in doing so, provide an assessment of the adequacy of pasture as a nutrient source for grazing dairy cows.

2.6.1 Dry matter intake

Milk production is highly correlated with DMI (Holmes et al., 2002). In pasture-based grazing systems, DMI is conceded as the factor restricting milk production to the greatest extent (Bargo et al.,2002; Boudon et al., 2009; Kolver & Muller, 1998; Kolver et al., 2002). The collective results from various studies suggest that a "ceiling" pasture DMI limits herd milk production to around 30 kg/day, and 2.3-2.5 kg MS (Kolver, 2003), although individuals can produce much more.

In comparing the performance of dairy cows fed a TMR with those grazing pasture, Kolver and Muller (1998) identified the potential level of milk production that pasture may facilitate, and in doing so, highlighted the extent to which pasture DMI constrains milk production. The difference is noteworthy; the cows offered the TMR averaged a DMI of 23.4 kg/day and daily milk yield of 44.1 kg, while pasture-fed cows had an average DMI of 19.0 kg DMI and daily milk yield of 29.6 kg/day. The lower DMI accounted for 61% of the 14.5 kg difference in milk production and, 90% of the difference in milk production could be accounted for, without invoking inadequacies in the nutritional value of the pasture-only diet. The main purpose of providing cows feed in addition to pasture (i.e. supplementary feeds), therefore, is to increase total DMI and energy intake to enhance production (Peyraud & Delaby, 2001; Stockdale, 2000b).

The DMI of pasture depends on the size and breed of the cow, as well as the quantity and quality of pasture available, with PA exerting the greatest effect (Wales et al., 1998). The increase in DMI with increasing PA is linear to a point and then diminishes at very high PA. For example, Wales et al. (1998) reported a linear increase in DMI from 8.0 to 14.6 kg DM/cow/day, as herbage allowance increased from 15 to 40 kg DM/cow/day. Within this range, DMI increased by 0.26 kg DM per kg increase in PA (Figure 2.10). This is almost identical to the response of 0.27 kg DM per kg increase PA reported by Stockdale (1985). Beyond a PA of 40 kg DM/cow/day, the DMI response to increased PA decreased to 0.19 kg DM/kg PA increase. At even higher allowances of 60-70 kg DM/cow/day, DMI was increased by a mere 0.09–0.13 kg DM/kg DM increase in PA.

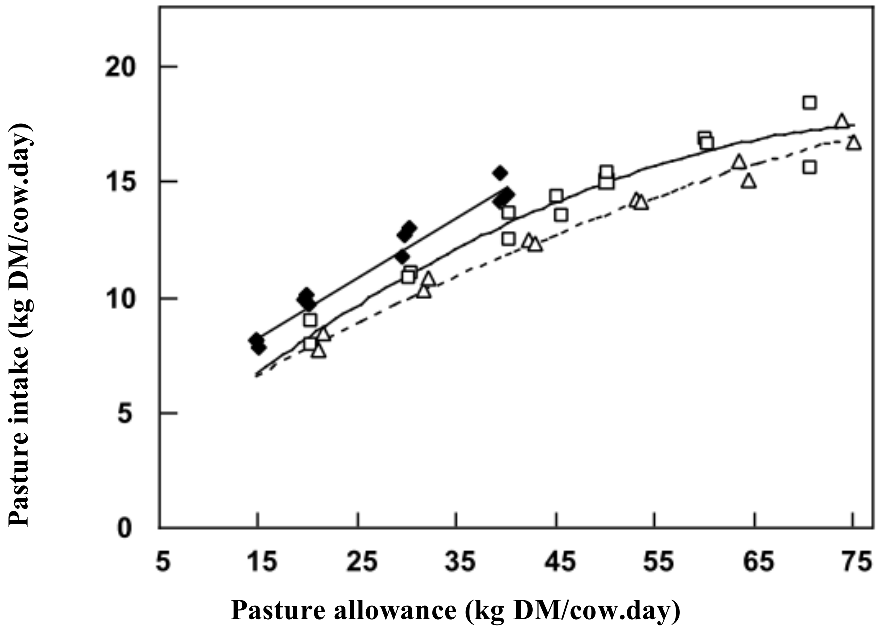

Figure 2.10: Relationships between pasture allowance and dry matter intake by cows grazing irrigated ryegrass-white clover (♦), high mass paspalum-dominant (□) and medium mass paspalum-dominant (Δ) pastures (Wales et al., 1998).

Despite the increase in DMI with greater PA, it is not practical to allocate such high PA to grazing dairy cows because, as PA increases, there is a simultaneous decline in the utilisation of that pasture. Wales et al. (1998) reported a 39% increase in PGR mass (from 1800 to 2500 kg DM/ha) when the PA increased from 15 to 40 kg DM/cow/day and a decline in pasture utilisation from 54% to 37% (measured to ground level). As discussed previously, the management of PGR's is important to maintain pasture quality and nutritive value.

2.6.2 Carbohydrates

Though energy can be derived from all organic matter, the major ME source for cows (~70%) comes from carbohydrates (Moran, 2005). Carbohydrates constitute the main precursors of fat and lactose in milk (Holmes & Wilson, 1984).

Carbohydrates may be classified as structural or non-structural (NSC's). The cell wall of the plant is made up of structural carbohydrates, mainly cellulose and hemicelluloses. Inside the cell wall, carbohydrates are primarily water soluble sugars (WSC's), with a small amount of starch stored in the seed head of grasses. Collectively, the starch and the WSC's comprise the highly digestible NSC's.

The structural carbohydrates form the basis of fibre, which is required by the pasture for structural integrity and required by the cow to stimulate rumen activity and to provide energy. Neutral detergent fibre is one measure of structural carbohydrates and quantifies the hemicellulose, cellulose and lignin fibre fractions. Though lignin is not a carbohydrate, it is an important component of the plant, as it binds to structural carbohydrates and proteins, making them less accessible to rumen enzymes, and therefore, less digestible (Moran, 2005).

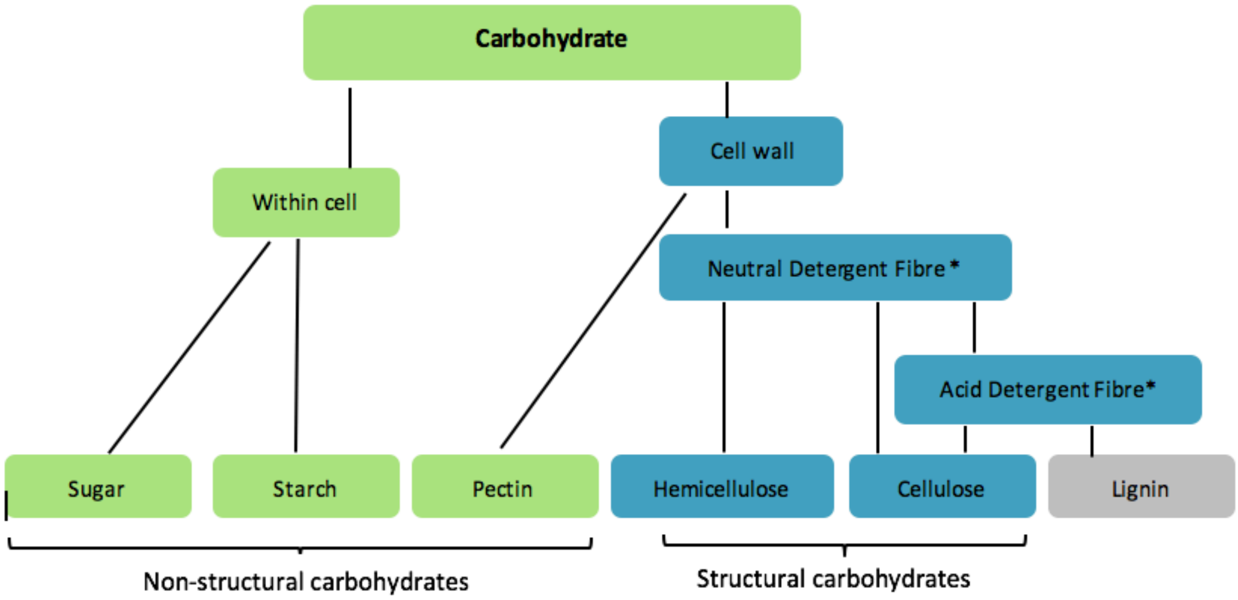

Figure 2.11: Carbohydrate classifications (Moran, 2005).

Fresh pasture, in contrast to a formulated TMR, is characterised by a high NDF to NSC ratio (Table 2.2; Kolver et al., 2000). In comparisons of pasture and TMR, pastures have far higher concentrations of crude protein and NDF, and far lower concentrations of NSC, despite having the same amount of ME (Table 2.2; Kolver et al., 2000).

Table 2.2: Mean annual nutrient composition of a pasture diet and TMR diet (Kolver et al., 2000).

(% DM)	Pasture	TMR
ME (MJME/kg DM	11.7	11.8
Crude protein	24.8	18.1
Neutral detergent fibre	42.6	30.6
Acid detergent fibre	21.8	19.4
Non-structural carbohydrate	10.8	28.1
Fat	4.5	5.6
Ash	10.6	12.3

Many studies have investigated the effect of carbohydrate type on the net energy output in milk in moderate production (< 40 kg of milk/d; 3 kg of fat and protein/d), pasture-based dairy cows (Carruthers et al., 1997; Roche et al., 2010; Higgs et al., 2013., Macdonald et al., 2017). Changing the source of energy from NDF to NSC, whilst keeping ME intake constant, had only small effects on milk production (Roche et al., 2010) and primarily in milk volume and the protein to fat ratio in the milk. This supports the premise that it is ME intake that constrains milk production rather than the source of that ME (i.e. carbohydrate type).

2.6.2.1 Fermentation of carbohydrates

Cows, as ruminants, digest their food through fermentation. This process requires microorganisms in the rumen that "adhere to particles of roughage, and gradually erode out the digestible material" (Orskov, 1998). The fermentation substrate (for example NDF or NSC) dictates the predominant microorganism populations in the rumen. Although pyruvate is the intermediate fermentation product of all carbohydrates, different microorganism populations produce different end-products (volatile fatty acids, VFA's) of fermentation (Figure 2.12).

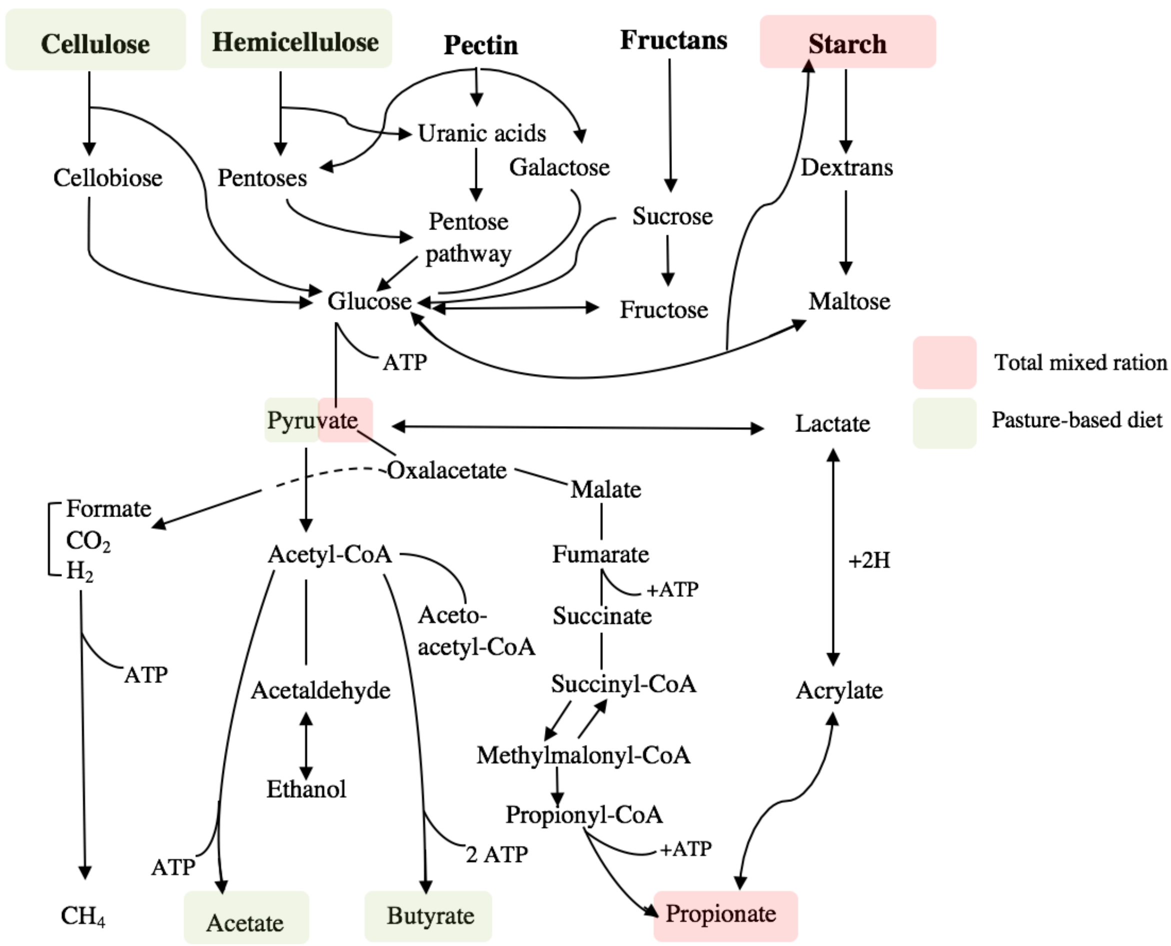

Figure 2.12: Pathways of carbohydrate metabolism in the rumen (van Soest, 1994).

The fermentation of NDF primarily stimulates the production of acetate and butyrate in the rumen, whereas the fermentation of NSC, which constitutes a major portion of the carbohydrates in a TMR, results in the production of more propionate and less acetate (Moran, 2005). Acetate and butyrate are the building blocks of de novo fatty synthesis; propionate is the primary source of carbon for gluconeogenesis in the ruminant liver. Greater amounts of propionate result in an increase in insulin secretion by the ruminant, which increases the uptake of amino acids by the mammary gland and reduces the release of fat from adipose stores (Rius et al., 2010). Changes in fatty acid biohydrogenation in the rumen during the fermentation of NSC can also reduce milk fat production (Griinari et al., 1998). Therefore, the diet that increases propionate production (the TMR) will likely increase the milk protein concentration and reduce the milk fat concentration, with the converse being true for high NDF diets, like fresh pasture. However, the effect on the milk fat to protein ratio is small and in studies where ME intake has been controlled, altering the proportion of structural carbohydrate to NSC, has not changed the net energy output in milk.

2.6.3 Summary

From a nutritional perspective, pasture is an adequate feed for moderate-yielding dairy cows (< 30 kg milk/d or less than 2.5 kg milk fat and protein/d; Kolver & Muller, 1998). Provided it is well managed (i.e. quality is maintained and regrowth potential ensured) and SR is appropriate (so that feed demand can be adequately met through pasture supply), it is a well-balanced feed and will meet cow nutrient requirements year-round.

The main factor restricting milk yields in a pasture-based system is ME intake, which is largely the result of the constrained DMI when cows are grazing pasture, compared with a TMR system. Even if cows could consume enough pasture DM to facilitate high milk production, it would not be feasible, as unrestricted PA implies low pasture utilisation (Christie et al., 2000). The main factor limiting DMI of cows grazing pastures, therefore, is management, as the farmer must restrict the allocation of pastures to ensure adequate pasture growth and quality in the future (Sheahan et al., 2011). The primary focus of grazing management should be the optimisation of the quality and quantity of pasture grown and harvested by the cow. The potential for milk yields above 30 kg/day, therefore, requires the provision of supplementary feeds to provide additional ME.

Until a significant proportion of the diet consists of supplementary feeds (>30 %, Roche, 2017) the logic behind providing supplementary feeds to ‘complement’ a pasture diet and overcome nutritional insufficiencies, is unlikely to result in a significant effect on milk production. This has been demonstrated in several experiments where a proportion of pasture in the diet was substituted for high NSC content feeds (e.g. maize grain), while total ME intake remained constant. The effects on milk composition and yield of changing the diet to increase NSC concentration were minor. A supplementary feed therefore, should only be provided to grazing cows where seasonal feed deficits are having a negative effect on the efficiency and profitability of the system.

2.7 Supplementary feeds

Temperate pasture is a nutritionally well-balanced feed (Roche, 2017). In general, it has adequate levels of high quality protein, reasonable levels of NSC, minerals and vitamins and, although it is moderate to high in fibre (i.e., 35-50% NDF; Roche et al., 2009), the fibre is highly digestible, making pasture as dense in ME as wheat or barley when in a leafy state. As a result, a pasture-only diet provides adequate nutrients to support moderate milk production. The seasonality in pasture growth profiles, however, can result in too little pasture available to meet cow demand. It is in these feed deficit situations that supplementary feeds are often imported to allow the farm to maintain SR and animal output.

For the potential economic benefit of imported supplement to be assessed, the animal response from the additional feed in either milk production, body condition, or reproduction must be measured. For the feeding of supplements to be profitable, the benefits obtained from the response must outweigh the cost of the supplement and the associated costs of feeding the supplement, including milking additional cows, labour, depreciation, and farm capital costs.

2.7.1 Responses to supplementary feeds.

The responses of dairy cows to supplementary feeds, can be classified as immediate or deferred. The effects of supplementary feeds on the body condition and reproduction of animals, are referred to as deferred responses to supplements (Kellaway & Porta, 1993), as they cannot be accurately assessed in the short-term. These effects are also small and, therefore a focus on milk production responses to supplementary feeds is the most practical way for farmers to make an economic assessment of supplement use.

The MR to supplementary feed is the extra yield of milk and milk components produced from the most recent increment of supplementary feed consumed (Heard et al., 2017). The MR to supplementary feed is considered an intermediate response. Measured daily, the MR is a good indicator of whether it is profitable to be feeding a certain level of supplementary feed, given current feed and milk prices.

While, in theory, the addition of a kilogram of supplement with an estimated ME of 12 MJ/kg DM (e.g. cereal grain) should support an increase in milk production of ~2 L/day (Roche et al., 2017), responses are generally less than this (Figure 2.13). Furthermore, they vary considerably. Bargo et al. (2003) reviewed the intake of supplements by high-performing (producing > 28 kg milk/day) dairy cows consuming predominantly pasture diets. They reported an average MR of 1 kg milk/kg concentrate eaten, with a range from 0.60 (Sayers, 1999) to 1.45 kg milk/kg of concentrate (Gibb et al., 2002). A similar, earlier review, however Rogers, (1985) reported much lower MR's, with an average 0.51 L milk/kg concentrate eaten, and a greater range in responses from 0 to 1.75 L milk/kg concentrate eaten. Although reported in litres, this is a fair comparison and highlights the variability in MR to supplementary feeds. Furthermore, the average response to supplements estimated for commercial farms (Ramsbottom et al., 2015) was 30% lower than that reported by Bargo et al. (2003).

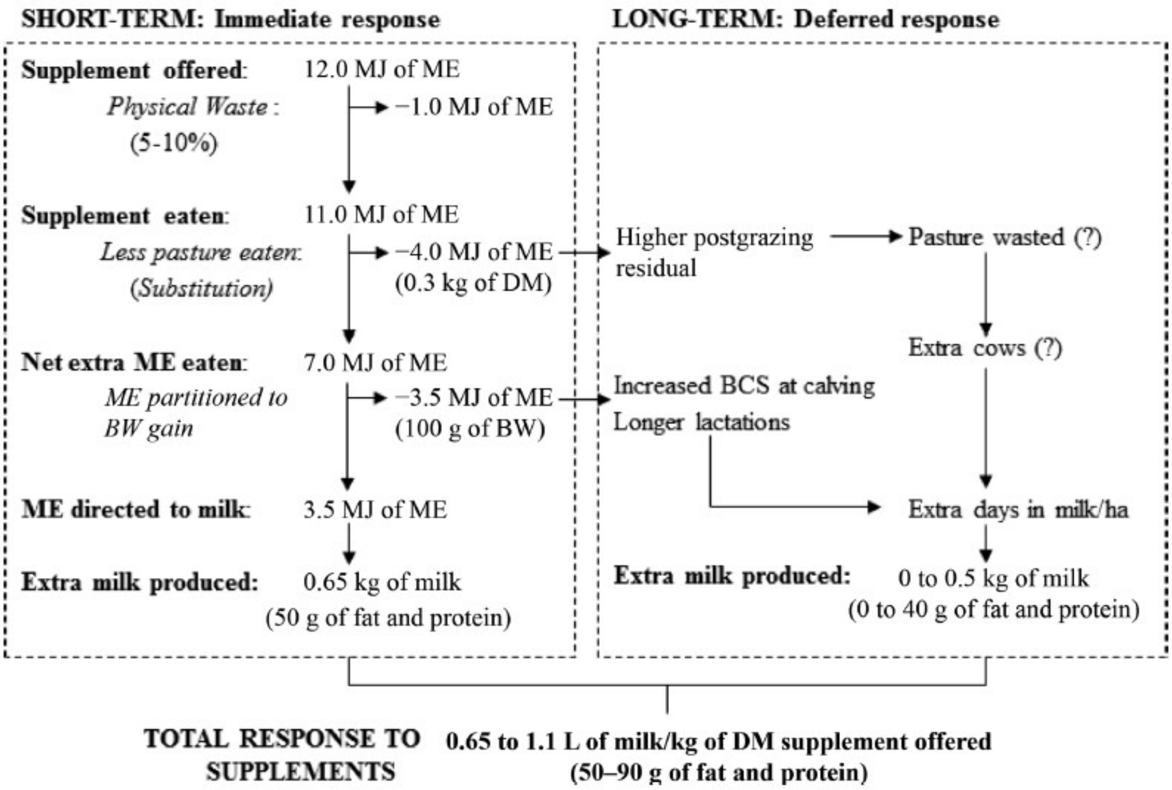

Figure 2.13: Schematic to depict the short-and longer-term responses to 1 kg of high-quality supplement DM offered/cow (Roche et al., 2017).

There are several interacting factors that contribute to the variation in MR to supplements. In the regression equation: MR = 2.62 – 0.80 (± 0.216) substitution – 0.28 (± 0.084) season – 0.34 (± 0.086) body condition [100R2 = 62.9 (P < 0.01); r.s.d. = 0.23; CV = 29.6%], Stockdale (2000) defined the main factors as:

1. Substitution (i.e., cows refuse some pasture when offered supplementary feeds);
2. Season; and
3. Body condition score.

Of these factors, substitution has the largest effect on the MR to supplement feeds by cows consuming a predominantly pasture diet. This will be discussed further.

2.7.2 Pasture substitution

A major source of the variation in MR to supplementation, comes from the substitution of a supplementary feed for pasture (i.e. cows refuse some pasture when offered supplementary feeds; Stockdale, 2000; Kellaway & Harrington, 2003). Due to substitution, total DMI increases when supplementary feeds are added to a pasture-only diet, but pasture DMI declines. Consequently, pasture, that would otherwise have been eaten, remains *in situ*. The substitution rate (SbR) is the amount of pasture rejected per kg of supplement offered and is, at least in part, explained by a reduction in grazing time. Bargo et al., (2003) reported that for every additional kg of DM concentrate offered, grazing time decreased by 12 minutes. This was subsequently confirmed by Sheahan et al., (2011).

The substitution of pasture for supplementary feeds can substantially diminish the MR from feeding that supplement (Leaver et al., 1968; Stockdale, 2000b). Therefore, high SbR's are economically disadvantageous, as they reduce the revenue generated from the provision of supplementary feed. There is a general consensus in the literature that the relationship between SbR and MR, as an increasing proportion of the diet consists of supplementary feeds, is negative. However the slope of the relationship varies (Figure 2.14).

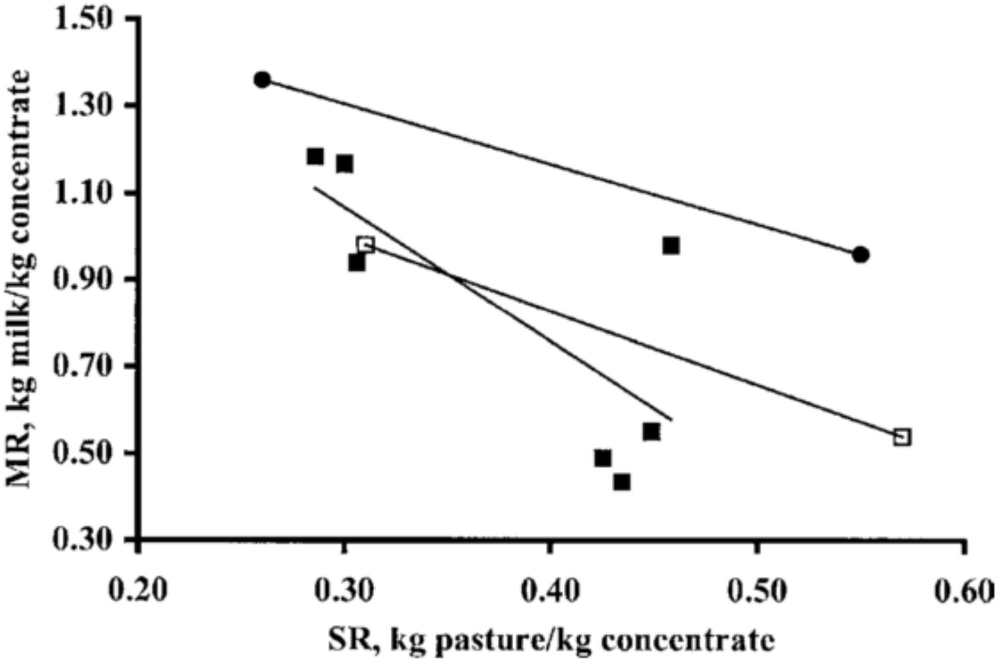

Figure 2.14: Relationship between MR and SbR by grazing cows supplemented with concentrate on studies evaluating the effect of pasture allowance (● Bargo el al., 2002; □ Robaina et al., 1998; ■ Stockdale 1999a).

The variation in this relationship stems from many complex factors interacting to affect SbR. These include:

- Relative feed deficit (Penno, 2002);
- Pasture allowance (Grainger & Mathews, 1989);
- Stage of lactation; (Bargo et al., 2003);
- Pasture quality (Bargo et al., 2003);
- Genetic merit of the cow (Peyraud & Delaby, 2001); and
- Concentrate type.

Of these factors, the RFD of the cow (i.e., the satisfaction of nutrient requirements that the current diet provides, relative to the feed required to fully satisfy nutrient requirements) has the largest effect on SbR. Quantification of the RFD is, therefore, useful in assessing the economics of feeding supplements, because, as well as its influence on SbR, it has a large effect on the partitioning of energy within the cow (i.e., to milk production or to liveweight gain) and thus on the MR to supplementation (Baudracco, 2011).

The SbR and the RFD are interrelated (Penno, 2002), therefore, the aforementioned factors that influence the SbR, do so indirectly through their influence on the RFD. The RFD will be discussed further and four key factors that influence RFD (and thus SbR) will be considered.

2.7.3 Relative feed deficit

The RFD of a cow is the ability of the current diet to satisfy nutrient requirements relative to the requirement for that cow to produce to its potential production level (Penno 2002). In simpler terms, it is how hungry the cow is before any extra feed is provided.

The scale of the SbR is largely determined by the RFD. Data from multiple experiments in grazing systems (76 data sets) were collated to identify the key variables affecting SbR when concentrate supplements were fed (Stockdale, 2000). The analyses highlighted the significance of the RFD on SbR by comparing SbR's at different levels of unsupplemented pasture intake (i.e. different RFD's). In that report, the SbR increased by 0.21 kg pasture DM/kg DM concentrate increase for each additional kg DM of pasture/100 kg liveweight in the unsupplemented diet: for a 500 kg cow, the cow refused an additional 0.21 kg pasture when provided with 5 kg DM supplement. Put simply, the less hunger (lower RFD) a cow is experiencing prior to the provision of supplement, the higher the SbR.

When a severe RFD exists, the substitution of pasture with supplements may be a desirable pasture management tool, as it would allow farmers to increase their PGR's to target levels (see section 3.3). When cows are adequately fed on pasture, then RFD is low. And, if farmers are achieving target grazing residuals, then any addition of supplement will cause unwanted substitution of pasture and result in reduced pasture utilisation and an increase in residuals beyond target. If the pasture that is substituted with supplementary feeds, is not conserved as silage or hay, it will be wasted. Minimising SbR should be a priority when feeding supplements for the dual purposes of improving utilisation of both pasture and the supplement, resulting in an increased MR.

The main determinant of the RFD magnitude is the PA.

2.7.4 Pasture allowance

The PA relative to the animal's requirements at the time that a supplementary feed is offered, determines the RFD; thus, has a large effect on the SbR. At lower PA's, the SbR is lower than it is at higher PA's. A summary of studies in which cows were allocated low PA's (i.e., ranging from 7.6 to 22.2 kg DM/cow/day from ground level), had an average SbR of 0.19 kg DM pasture/kg DM concentrate (Grainger & Mathews 1989; Meijs & Hoekstra 1984; Robaina et al. 1998; Stakelum 1986). The minimum SbR in these studies was zero, and the maximum was 0.31 kg DM pasture/kg DM concentrate. In comparison, at high PA's (24 to 42.3 kg DM/cow/day from ground level), the average SbR was 205% greater (0.58 kg DM pasture/kg DM concentrate), and ranged from 0.43 to 0.69 kg DM pasture/kg DM concentrate. This difference in SbR at low and high PA's can, for the most part, be explained by the reduction in RFD.

When the SbR is lower (at a low PA), the relative increase in total DMI when supplements are consumed is greater than when the SbR is higher (at a high PA). This was demonstrated in a study where total DMI was compared between cows offered low (25 kg DM/cow/day to ground level) and high (40 kg DM/cow/day) PA's (Bargo et al., 2002). Although total DMI increased in both scenarios, the increase in the low PA (low SbR; 0.26 kg pasture/kg concentrate) treatment was 61% greater than in the high PA (high SbR; 0.55 kg pasture/kg concentrate) treatment (5.8 vs. 3.6 kg/d). Because DMI is the factor most limiting milk production, lower PA's (and lower SbR's) will result in comparatively higher MR to supplementary feeds, in a pasture-based system.

In addition to DMI, it has been suggested that at high PA's, pastures are taller and, therefore, more prone to being trampled and fouled than shorter pastures (Stockdale, 2000b). The physical effect of trampled pastures (flattened, closer to the ground) makes them less accessible to cows, and causes them to be less palatable, and thus contributes to higher SbR's.

In summary, PA is the chief determinant of cow RFD, dictating the SbR when supplements are offered to grazing cows. However, Stockdale (2000) noted that PA interacts with season of the year and/or stage of lactation in determining SbR. This effect needs to be further discussed.

2.7.5 Effects of season of year and/or stage of lactation on the RFD, SbR and MR to supplementary feeds

It is almost impossible in a seasonal calving system (pasture-based system) to separate season and stage of lactation (SOL) effects. The seasonality of pasture-based dairy systems means that the entire herd are always in a similar SOL and, these stages occur at certain times of the year. For example, early lactation will always occur in the spring and mid-lactation in the summer. In contrast, calving in the TMR system is not restricted to one period of the year, as there is no need to match maximum pasture growth with the period of maximum energy demand; feed of consistent quality is available year-round. Thus, the effects of SOL and season on the MR to feed in pasture-based systems are confounded.

The partitioning of the absorbed nutrients to either milk production or liveweight gain, influences the magnitude of both the immediate and deferred MR to supplements. This partitioning of nutrients to different processes is influenced by the SOL (Stockdale & Trigg, 1989). In early lactation (spring in a pasture-based system), energy partitioning towards milk production is favoured over liveweight gain. As lactation progresses liveweight gain is increasingly prioritised, and eventually, favoured over milk production.

The greater proportion of energy and nutrients partitioned towards milk production rather than body tissue reserves in early lactation has long been used as a reason to support the assumption that MRs to supplementary feeds should be greater in early than in late lactation (Stockdale & Trigg, 1985; Stockdale & Trigg, 1989, Kellaway& Porta, 1993). However, a review of experiments (Penno, 2002) demonstrated that despite the milk yield decline as SOL progressed, there was little effect of SOL on the MR to supplements (Table 2.3). Cows in early, mid and late lactation exhibited average MR's of 54, 39 and 56 g MS/kg DM supplement.

Table 2.3: A comparison of marginal milk production response to supplementary feeds reported from experiments with early, mid and late lactation cows published since 1979 (Penno 2002).

Stage of lactation	Early	Mid	Late
Studies	15	13	12
Observations	46	39	46
Performance of unsupplemented cows			
Pasture DMI (kg/c/d)	12.2 (±3.8)	11.3 (±3.0)	10.5 (±2.9)
Stage of lactation (days-in-milk)	42 (±26)	105 (±53)	210 (±27)
Milk yield (kg/c/d)	18.9 (±4.5)	14.4 (±4.1)	10.3 (±2.9)
Liveweight (kg)	489 (±34)	479 (±47)	475 (±41)
Marginal responses to supplements			
Milk (kg/kg DM)	0.7 (±0.8)	0.6 (±0.7)	0.8 (±0.4)
Milksolids (g MS/kg DM)	54 (±30)	39 (±49)	56 (±33)
Milksolids (g MS/MJME)	4.2 (±2.4)	3.8 (±3.9)	4.6 (±2.8)

When interpreting the MR's to supplementary feeds at different SOL, the RFD should be taken into account. Penno (2002) attributed the inconsistent effects of SOL on the MR to supplementary feeds in his review, to the different RFD's immediately before the treatments were imposed. The inconsistency was a result of a common restricted feed allowance imposed at every SOL. For example, in the comparison of early and late lactation cows by Stockdale et al. (1987), the cows were consuming a severely restricted allowance of pasture (about 7 kg DMI cow/d) plus different quantities of concentrate supplementary feeds. Therefore, the cows in early lactation, due to their higher MS yield (~ 500g MS cow/d), had a greater RFD than cows in late lactation. Similarly, Stockdale and Trigg (1989) imposed a common feed restriction and reported that responses of late-lactation cows to feed restrictions were less than the responses of early-lactation cows. In support of Penno's theory, as the RFD declined (due to increases in pasture offered to the control cows), the MR to supplementary feeding also declined (Stockdale & Trigg, 1989). Furthermore, in a later experiment by Grainger (1990), who had smaller RFD's, there was little difference in the MR to supplementary feeds from early and late lactation cows.

In summary, the effects of SOL on the MR to supplements are inconsistent in the literature and this may be attributed to the lack of consideration for the RFD in experiments.

2.7.6 Pasture quality

Though SOL and season effects are often confounded in experiments of seasonal dairy cows grazing pasture, pasture quality, which changes throughout the year is one example of a season effect, and may influence the RFD. When the DMI of a grazing dairy cow is restricted, the SbR and thus the RFD is likely to be greater. Stockdale (1999b) attributed the increased MR to supplementary feeds in the summer and autumn to the lower quality of the pasture on offer during the summer (8.7 MJME/kg DM) and autumn (9.2MJME/kg DM), compared with the pasture offered during the spring (l0.3 MJME/kg DM). While Penno (2002) reported that season did not affect SbR, higher SbR were recorded when higher pasture quality or allowance enabled the unsupplemented cows to achieve higher DMI from pasture than at other times of the year. As discussed in section 3.1 pasture is usually of the highest quality in spring and lowest in summer. Thus, at the same pasture allowance relative to milk production ability, the RFD should be less in spring and SbR highest. Previous research has provided conflicting evidence, with no consistent patterns emerging on the effects of season or SOL on the MR to supplementary feeding.

1.1.1 Genetic merit

Cow genotype influences potential milk yield (Horan et al., 2004; Linnane et al., 2004), the demand for nutrients and energy and, therefore, influences a cow's RFD (Baudracco, 2011). For example, a cow with the genetic potential to produce 30 kg milk, consuming a diet that allows the production of 25 kg milk, has a higher demand for nutrients and energy and thus a larger RFD than another cow consuming the same diet, but with the genetic potential to produce 27 kg milk. This greater RFD results in lower SbR's and higher MR's to supplementary feeds from the larger and higher producing cow (Baudracco, 2011).

2.7.7 The effect of RFD on MR to supplementary feeds

As discussed, the RFD influences the MR to supplementary feeds. Penno (2002) demonstrated the effect of the severity of the RFD on both marginal and total milk production responses to supplementary feeds, by imposing different degrees of feed restrictions on groups of cows. He defined the RFD of each group as the reduction in MS yield (g MS/cow/day) that occurred upon the initiation of the feed restriction. A greater RFD (defined by a large reduction in MS yield when cows were restricted), resulted in a greater MR to supplements, relative to a lesser RFD (defined by a smaller reduction in MS yield during a feed restriction; Figure 2.15). A 1.0 kg MS/cow/day reduction in MS yield (or a 1 unit increase in severity of RFD) was linked to an immediate increase in the marginal MS response of 9 g MS/MJME supplement.

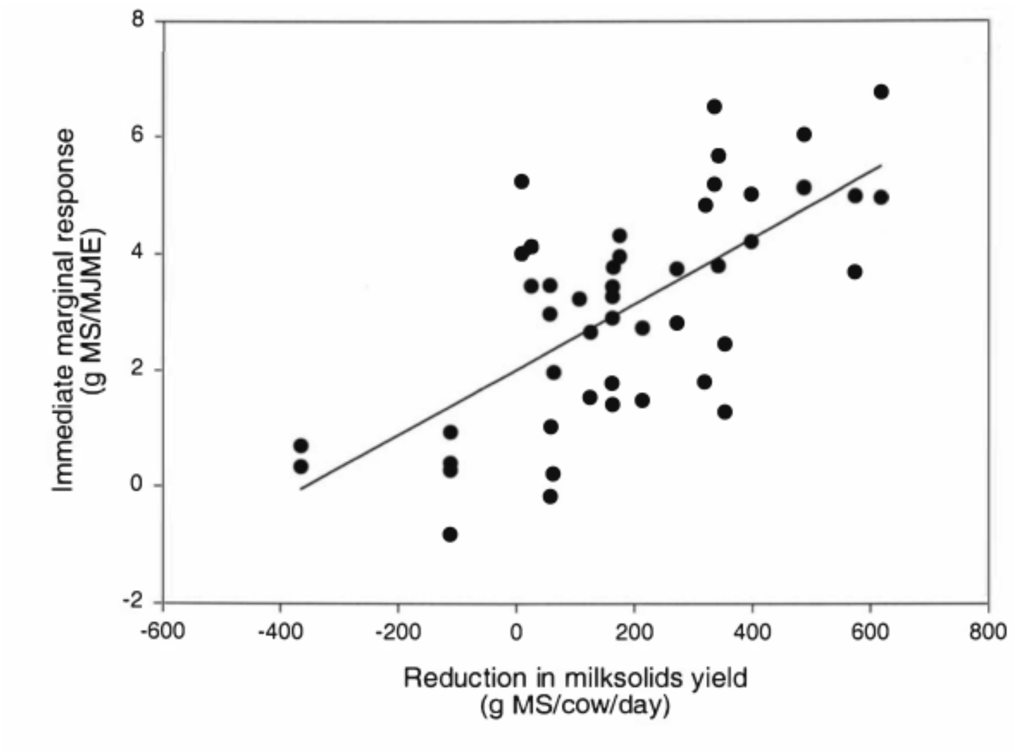

Figure 2.15: The effect of the decline in milksolids (MS) yield of the unsupplemented cows that occurred as restricted feeding was imposed (as a measure of the relative feed deficit) on the immediate MS response to supplementary feeds. Immediate marginal response (g MS/MJME) = 2.02 (±0.26) + 0.006 (±0.0009) reduction in MS yield (g/cow/day); Adjusted R^2=0.44; r.s.d. = 1.38 (Penno, 2002).

The provision of supplementary feeds offered, if any, should, therefore, be determined and adjusted based on the RFD, as this will ensure that SbR, pasture utilisation and the MR to supplements are maximised (Penno, 2002; Baudracco, 2011; Roche & White, 2012).

2.7.8 Quantifying the relative feed deficit

To determine the RFD of a cow and, thus, estimate the MR to supplements, farmers must know the difference between the energy required to achieve maximum milk yields, and the actual ME intake. Quantifying the RFD is difficult because the DMI of grazing dairy cows cannot be accurately determined and RFD varies on a per cow basis.

We know that the RFD is reflected in the SbR, and that the substitution of pasture with supplementary feeds results in higher PGR's and a decline of overall pasture utilisation (Bargo et al., 2003; Stockdale, 2000b). McEvoy (2008) reported that for every 1 kg increase in concentrate offered, PGR height increased by 10 mm. This is in line with the average 12 mm increase in PGR height per kg concentrate reported by Kennedy et al. (2007). This decline in pasture utilisation was identified as a primary contributor to the lower MR to supplements on commercial farms (Ramsbottom et al., 2015). Thus it has been proposed that PGR's may be used as a proxy to estimate the RFD (Roche & White, 2012) and to allow practical daily estimates of the MR to supplementary feeds. However, the relationship between PGR's and the MR to supplement has not yet been defined.

2.8 Conclusions

For supplementary feed usage to be profitable in a pasture-based system, the MR obtained must exceed the cost of feeding the supplement. Variation in reported responses is high, as many complex factors interact to influence the MR, predominantly (as identified by Stockdale, 2000) season, body condition score of the cow, and the substitution of pasture for supplements. Minimising the SbR should be a priority when feeding supplements for the dual purposes of improving the utilisation of pasture and the supplement.

The RFD is the primary determinant of SbR; however, it is difficult to accurately quantify. It has been proposed that the PGR could be used to estimate the RFD and, thus, predict the MR to supplementary feeds. However, the relationship between the PGR and the MR to supplement has not been adequately quantified.

2.9 Thesis objectives

Although models exist to predict the MR to supplementary feeds, they often do not consider how pasture-level variables and grazing management influence this response. These variables contribute to the large variation in reported responses to supplements. The relationship between pasture variables (e.g. PGR height or mass) and MR to supplement has not been adequately quantified; nevertheless, it may provide a tool for farmers to estimate the RFD of the herd and facilitate better decision making around feeding supplements. Therefore, the objectives of this thesis are:

1. To develop a research database including pasture, cow and supplementary feed factors to determine how pasture management can influence the marginal milk production response to supplementary feeds
2. To determine, using the PGR, the effect of the RFD on the MR of grazing dairy cows to supplementary feeds.

2.10 Hypothesis

I hypothesise that the MR to supplementary feeds is affected by pasture utilisation and will decrease with increases in the pre-supplementation post-grazing residuals.

Chapter 3 Materials and methods

3.1 Database construction

3.1.1 Literature review and data entry

A computerised literature search initiated the collation of the data set. This involved library searches of relevant journals including: Journal of Dairy Science, Journal of the Science of Food and Agriculture, Journal of Dairy Research, Australian Journal of Experimental Agriculture, Irish Journal of Agricultural Research and Proceedings of the New Zealand Society of Animal Production.

Key words used in the search (in different combinations) included: Milk response, supplementary feeds, grazing-systems, pasture-based, dairy cows.

Following the initial search, a systematic review of citations in papers was undertaken to identify other relevant papers.

In all, approximately 70 English-language published papers were reviewed with published dates from 1985 to 2016. Of these papers, only those that satisfied the following predetermined criteria, were included in the original dataset. These criteria included:

1) Temperate regions and temperate sward species;
2) The base-feed of the diet was pasture, grazed in situ by dairy cows;
3) Pasture variables were measured in the study (i.e., pre-grazing height/mass and post-grazing height/mass);
4) Information on season, country, stage of lactation and length of trial were provided
5) Within experiment comparison of a least one supplement level to the control (i.e., pasture-only) diet was made with the same experimental conditions

Trials were ineligible for inclusion at this initial stage if:

1) The cows were housed and received their pasture allowance already cut (i.e. didn’t have to graze)
2) No pasture variable measurements were provided.

The result of this selection was 25 papers, representing 90 treatment means.

3.1.2 Data filtering

Stage 1

The data filtering stage was extensive. The first step was to identify studies already in the dataset in which insufficient information was provided to allow the calculation of pasture variables. Often, only pre-grazing herbage mass/height was reported, and not post-grazing herbage mass/height, without enough extra information provided (for example, area allocated, number of cows, allowance per cow etc.) to allow the calculation of the missing measurement. If everything else was present (i.e., to allow the marginal milk production and dry matter responses to supplements to be calculated), the study was retained in the database. In some studies, pastures were managed to be homogenous pre-treatment, confounding the effect of the PGR and PA, because high PA led to greater PGR. These studies were excluded from the database.

Stage 2

Many published studies reported more than one experiment. The next step was to identify unsuitable treatments/experiments, within studies, to be excluded from the dataset. Examples of the rationale behind the exclusion of experiments and treatments within studies, from the dataset can be found in Table 3.1.

Table 3.1: Example of the rationale behind exclusion of experiments and treatments within studies, from the dataset.

Reference	No. Treatments Removed	Reason for Exclusion	No. Treatments Remaining
Burke et al., 2008	1	The treatment removed had a much greater pasture allowance than the other treatments.	2
Chaves et al., 2006	2	More than 1 supplement type fed together (either maize silage + barley, or maize silage and cottonseed meal or maize silage + sulla silage)	3
Kennedy et al., 2007	12	Only period 1 of the trial kept in the database. This experiment measured the *immediate* response to concentrate supplementation, while in period 2 and 3, measurements continued as concentrate supplementation ceased to measure the subsequent and total lactation effect of supplement use. To ensure consistency across the database, only immediate response to supplement use was included.	6
Penno et al., 2006	4	In experiment 2, an ad libitum pasture treatment was included in every season. This was removed as the restricted pasture treatment was used as the control to determine the response to supplementation.	
Reis & Combs, 2000	1/0*	An average pre-and post-grazing herbage mass was provided for the entire trial. Effect of treatment therefore, cannot be analysed	
Sairanen et al., 2006	3	In experiment 3 within the trial, no post-grazing sward heights/masses were recorded so no response can be observed	10

* Entire study removed from analyses of pasture variables, but included in the analyses of milk variables

Table 3.1 continued: Example of the rationale behind exclusion of experiments and treatments within studies, from the dataset.

Reference	No. Treatments Removed	Reason for Exclusion	No. Treatments Remaining
Stockdale, 1997a	6	More than 1 supplement type fed together	4
Stockdale, 1997b	3	More than 1 supplement type fed together	4
Stockdale, 2000	8	The excluded treatments were testing the hypothesis that the level of substitution with the feeding of concentrates would be influenced by body condition and liveweight. Supplementary feed level remained the same and liveweight and body condition remained constant	4
Wales et al., 2001	6/0*	Only pre-grazing height and mass were provided and insufficient other information available (e.g. area or stocking rate) to enable the calculation of post height/mass	6/0
Woodward et al., 2006	1	Pasture allowance was far higher than all other treatments (50 kg DM/ha vs 25 kg DM/ha)	5

* Entire study removed from analyses of pasture variables, but included in the analyses of milk variables

3.2 Calculations and data standardization

Some of the data were incomplete, which necessitated the following calculations or assumptions.

3.2.1 Fat corrected milk

Formula for 4% fat-corrected milk (FCM):

$$4\%\ \text{FCM} = [(0.4 \times \text{kg of milk}) + (15.0 \times \text{kg of fat})]$$

(Gains, 1928)

3.2.2 Substitution rate

The SbR is calculated as:

$$\mathrm{SbR} = \frac{\text{pasture DMI in unsupplemented treatment} - \text{pasture DMI in supplemented treatment}}{\text{Supplement DMI}}$$

(Bargo et al., 2003)

Therefore, a SbR less than 1 kg/kg supplement means that the total DMI of the supplemented treatment is higher than total DMI on the pasture only treatment. And a SbR equal to 1 kg/kg supplement, means that the total DMI on the supplemented treatment is the same as the unsupplemented treatment (i.e. the amount of pasture DMI refused is equivalent to the amount of supplement they consume (Bargo et al., 2003).

3.2.3 Pasture DMI

Where not provided, pasture DMI was calculated as:

$$(\text{pregrazing pasture mass} - \text{postgrazing pasture mass}) \times \left(\frac{\text{area grazed per day}}{\text{no. cows}}\right)$$

(Penno, 2002)

3.2.4 Standard errors.

It was necessary to include the pooled standard error of the mean (SEM) response variables per study, as a weighting factor for the data. Because measurements recorded were not consistent across studies, standard errors are not available for every response variable. For example, some studies reported only FCM, and thus have a SE for FCM, whilst in the majority, FCM was calculated, and therefore does not have a SE associated with it.

Calculations used to convert to SEM:

- SEM = standard deviation / $\sqrt{n}$
- SEM = standard error of the difference / $\sqrt{2}$

Where the experimental unit to determine n was

1) number of cows for milk production responses; and
2) duration of trial (days) for pasture variables.

3.3 Statistical analysis

3.3.1 Overall average marginal response to supplement

A meta-analysis to determine the marginal response to supplements for each measured variable across all the studies was undertaken using Random coefficient regression (St-Pierre, 2001) using GenStat 18.2[1]

Within each study, Treatment Groups were determined that, at each measurement time, had treatments that differed only in the amount of Supplement offered (Table 3.2).

Table 3.2: Example of the division of a study into Treatment Groups that were then analysed to determine the marginal responses to supplementary feeds. In this example, the Treatment Groups differ by pasture allowance.

Study: (Bargo et al., 2002)	**Season**	**Pasture Type**	**PA[1]**	**Supplement Type**	**Supplement offered**
Treatment Group 1	Spring/Autumn	SB/OG/KB[2]	26.7		0
	Spring/Autumn	SB/OG/KB	26.7	Concentrate	8.6
Treatment Group 2	Spring/Autumn	SB/OG/KB	48.9		0
	Spring/Autumn	SB/OG/KB	48.9	Concentrate	8.6

[1]Pasture Allowance

[2]Smooth bromegrass (*Bromus inermis* L.), orchardgrass (*Dactylis glomerata* L.) and Kentucky bluegrass (*Poa pratensis* L.).

[1] VSN International (2016). Genstat for Windows 18th Edition. VSN International, Hemel Hempstead, UK. Web page: Genstat.co.uk

In some of the studies these Treatment Groups were measured at more than one time during the study. These times are referred to as Repeated Measurements of the Treatment Group.

The random coefficient regression was fitted as a mixed model using REML, including Supplement DMI as a fixed effect and Study, Treatment Group within Study, Repeated measurement within Treatment Group, and Supplement DMI within each repeated measurement of each Treatment Group within Studies as random effects. The slope estimated in this analysis is the overall average marginal response to supplement DMI (i.e., it is the average slope, of all the treatment groups; Figure 3.1).

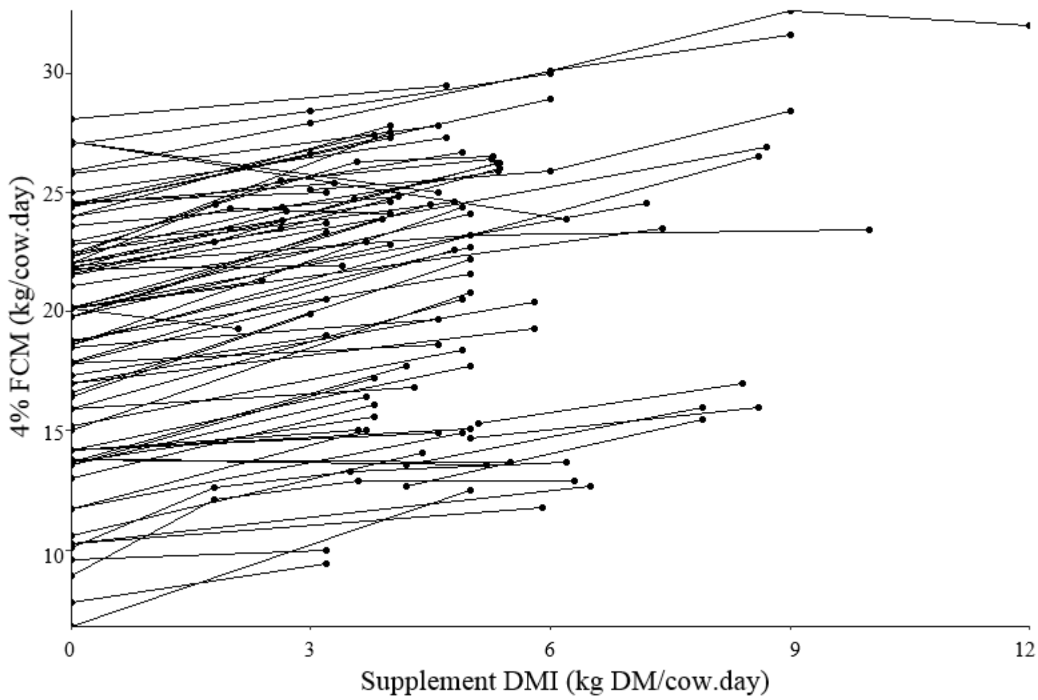

Figure 3.1: Figure to show the change in 4% FCM yield (kg) with increasing supplement DMI. The overall marginal 4% FCM response (non-weighted) generated from the analyses is the average slope of all the lines in this figure.

A weighted analysis was also undertaken using the mixed models described above, but weighting each data point by the reciprocal of the square of its SEM. The purpose of this is to give a greater weighting to data measured with more accuracy. This weighted analysis therefore excluded studies with no SEM available.

To estimate the marginal response for each Stage of Lactation (SOL) these meta-analyses (both unweighted and weighted) were extended by including (in addition to Supplement DMI), SOL, and the interaction of Supplement DMI with SOL as fixed effects in the model.

The treatments were grouped by stage of lactation for the following criteria:

1) Early lactation for cows less than 90 DIM;

2) Mid lactation for cows 91 to 181 DIM; and

3) Late lactation for cows more than 182 days in milk.

3.3.2 Associations between the marginal response to supplement and unsupplemented (control group) milk production , pasture DMI and post-grazing residual

These associations could not be determined in the overall meta-analysis because the unsupplemented data are used as independent variables for these associations, whereas in the overall analysis, variables consisting of supplemented and unsupplemented data are used as the dependent variable to determine the marginal response.

1. The marginal response to supplement for each measurement period for each Treatment Group within a study was determined using linear regression (both unweighted and weighted using the reciprocal of the square of the SEM) for each measured variable and including Supplement DMI as the independent variable. The slope of the fitted line is the marginal response to supplement.
2. Three variables were tested individually for associations with each marginal response variable:
    a. the unsupplemented data for the variable;
    b. the unsupplemented pasture DMI; and
    c. the unsupplemented post-grazing residual (height and mass).
3. Associations between the marginal responses to supplement and each of the unsupplemented variables were determined using another meta-analysis of the

marginal responses including Study, Treatment Group within Study, and Repeated measurement within Treatment Group as random effects, and SOL, Unsupplemented variable, and the interaction between SOL and unsupplemented variable as fixed effects;

a. Including only Unsupplemented variable for each Treatment Group. The slope of the fitted line is the change in the marginal response to Supplement for each additional unit of the Unsupplemented variable.
b. Including SOL and Unsupplemented variable (i.e. fitting parallel lines for each SOL with a common slope). The slope of the fitted line is the average change in the marginal response to Supplement across the stages of lactation for each additional unit of the Unsupplemented variable
c. Including the interaction of SOL and the unsupplemented variable (i.e. fitting lines with different slopes for each SOL).

4. These meta-analyses to determine associations between the marginal response to supplement and unsupplemented variables were repeated as weighted analyses, including studies for which SEM were available, including the reciprocal of the square of the SEM of the response to supplement from weighted linear regression.

Chapter 4 Results

4.1 Milk production responses to supplement

Results will be presented separately for the non-weighted and weighted analyses. The DMI and marginal milk production responses of dairy cows grazing pasture and consuming various supplementary feeds under a range of conditions (see Appendix 1 for details of individual studies) are presented in Table 4.1 and Table 4.2. These are the average marginal responses across different milk production categories, SOLs, and pasture and supplement allowances.

Non-weighted

The non-weighted analyses (Table 4.1) included 26 studies and 90 treatment means. Pasture and total DMI responses to supplement were -0.30 kg ± 0.02 kg pasture and 0.73 ± 0.02 kg total DMI for every kg supplement DM consumed. The results indicate that for every kg of supplement DM consumed, pasture consumed decreased by 0.3 kg, but total DMI increased by 0.7 kg ($P < 0.001$).

On average, the yields of total milk, 4% FCM, milk fat, milk protein, and MS all increased, by 0.67 ± 0.04 kg, 0.58 ± 0.04 kg, 20 ± 3.0 g, 25 ± 1.0 g, and 45 ± 3.0 g per kg supplement DMI eaten, respectively ($P < 0.001$).

Supplementary feeding affected milk composition. Milk fat decreased and milk protein increased with increasing DMI of supplementary feeds; for every kg supplement DMI, milk fat percent decreased by 0.04 ± 0.005 % and milk protein concentration increased by 0.02 ± 0.003 %. Therefore, the decrease in milk fat % was double the increase in milk protein %

Table 4.1: Average marginal dry matter intake (DMI) and milk production responses to supplement DMI in grazing dairy cows. Results are from a non-weighted analyses[1] of 83 treatments from 26 studies conducted between 1985 and 2008 and under a range of management conditions[2].

	Marginal Response	SE[3]	No. Studies	No. Treatments	*P*- value
DMI, kg/cow/d					
Pasture	-0.30	0.023	24	81	< 0.001
Total	0.73	0.022	24	81	< 0.001
Yield					
Milk (kg/cow/d)	0.67	0.038	25	83	< 0.001
4% FCM[4] (kg/cow/d)	0.58	0.037	26	90	< 0.001
Fat (g/cow/d)	19.5	1.74	25	83	< 0.001
Protein (g/cow/d)	25.0	1.20	25	83	< 0.001
Milksolids (g/cow/d)	44.8	2.83	25	78	< 0.001
Milk Composition, %					
Fat	-0.04	0.005	25	81	< 0.001
Protein	0.02	0.003	25	80	< 0.001

[1] Analyses not weighted by the reciprocal of the standard error of the mean squared.
[2] See Appendix 1 for details of the actual studies.
[3] Standard error of the mean
[4]4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).

Weighted

In the weighted analysis (Table 4.2), the subset of data to calculate the average 4% FCM response was considerably smaller than in the unweighted analysis; the number of studies included decreased from 26 to 8 and the number of treatments from 90 to 29. The FCM yield and the protein yield response to supplements was 10 and 20% greater than in the unweighted analysis: 0.64 ± 0.05 kg 4% FCM and 30g milk protein/kg supplement DMI. Results for the other milk production variables, however, were very similar to the non-weighted analysis.

Pasture and total DMI responses to supplement in the weighted analyses were also similar; for every kg of supplement eaten, pasture DM consumed decreased by 0.28 kg.

As MS were calculated as milk fat + milk protein, and total DMI as supplement DMI + pasture DMI, no SE's were available; thus, neither MS nor total DMI responses were included in the weighted analyses.

Table 4.2: Average marginal dry matter intake (DMI) and milk production responses to supplement DMI in grazing dairy cows. Results are from a weighted analyses[1] of 72 treatments in 22 studies conducted between 1985 and 2008 and under a range of management conditions[2].

	Marginal Response	SE	No. Studies	No. Treatments	*P*-value
DMI, kg/cow/d					
Pasture	-0.28	0.026	20	66	< 0.001
Total	-	-	-	-	-
Yield					
Milk (kg/cow/d)	0.65	0.046	22	72	< 0.001
4% FCM[4] (kg/cow/d)	0.64	0.052	8	29	< 0.001
Fat (g/cow/d)	19.4	2.53	12	32	< 0.001
Protein (g/cow/d)	29.6	1.62	12	32	< 0.001
Milksolids (g/cow/d)	-	-	-	-	-
Milk Composition, %					
Fat	-0.03	0.006	20	64	< 0.001
Protein	0.02	0.003	19	63	< 0.001

[1] Analyses weighted the result by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies.
[3] Standard error
[4] 4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).

4.2 Stage of lactation affected the DMI and milk production responses to supplement

The DMI response to supplementary feeding and the marginal responses in some of the milk production variables investigated were affected by stage of lactation. These effects are presented in Table 4.3 and Table 4.4.

Non-weighted

Summarising 26 studies (90 treatments) with supplement DMI ranging from 1.8 to 9 kg/d, the marginal 4% FCM response was 0.41, 0.63 and 0.72 ± 0.11 kg 4% FCM/kg supplement DMI in early, mid, and late lactation, respectively (interaction between stage of lactation and supplement intake: $P < 0.05$).

On average, marginal milk fat yield response to supplement also followed this trend (interaction between stage of lactation and supplement intake: $P < 0.05$) and the interaction between stage of lactation and supplement intake on the MS response tended ($P = 0.07$) towards significance. Summarising 25 studies (83 treatments) with supplement DMI ranging from 1.8 to 9 kg/d, the marginal milk fat yield response was 11.8, 21.9 and 25.6 ± 5.01 g milk fat/kg supplement DMI and the marginal MS response was 34.0, 48.1, and 54.0 g MS/kg supplement DMI in early, mid, and late lactation, respectively.

Stage of lactation did not affect the Pasture DMI responses to supplementary feeding in the in the non-weighted analysis (P = 0.11).

Stage of lactation did not affect the marginal production responses for the yields of milk ($P = 0.23$) or protein ($P = 0.44$) yield, nor did SOL affect the association between supplementary feeding level and milk composition.

Table 4.3: Average marginal dry matter intake (DMI) and milk production responses of grazing dairy cows to supplement DMI at different stages of lactation. Results from a non-weighted analyses[1] of 26 studies conducted between 1985 and 2008 and under a range of management conditions[2].

		Stage of Lactation				
		Early	Mid	Late	SED[3]	*P*-value
DM Intake, kg/cow/d	Pasture	-0.26	-0.37	0.27	0.061	0.11
	No. Studies	*9*	*10*	*7*		
	Total	0.13	0.12	0.13	0.011	0.628
	No. Studies	*9*	*10*	*7*		
Yield	Milk (kg/cow/d)	0.58	0.70	0.79	0.113	0.23
	No. Studies	*10*	*10*	*6*		
	4% FCM[4] (kg/cow/d)	0.41	0.63	0.72	0.109	< 0.05
	No. Studies	*10*	*11*	*7*		
	Fat (g/cow/d)	11.8	21.9	25.6	5.01	< 0.05
	No. Studies	*10*	*10*	*6*		
	Protein (g/cow/d)	22.4	25.5	27.3	3.66	0.44
	No. Studies	*10*	*10*	*6*		
	Milksolids (g/cow/d)	34.0	48.1	54.0	8.19	0.07
	No. Studies	*9*	*10*	*6*		
Milk Composition, %	Fat	-0.37	-0.03	0.60	0.012	0.12
	No. Studies	*10*	*10*	*6*		
	Protein	0.02	0.02	0.01	0.008	0.40
	No. Studies	*10*	*10*	*6*		

[1] Analyses not weighted by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies.
[3] Standard error of the difference
[4] 4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).

Weighted

In the weighted analyses (8 studies and 29 treatments), SOL affected the 4% FCM yield and pasture DMI response to supplement DMI; the effect on milk fat yield was no longer statistically significant (P = 0.44). The results indicate that the marginal FCM yield increase to supplement DMI was greater in autumn (late lactation) than in spring and summer, which were similar. The marginal 4% FCM yield response was 0.59, 0.48 and 0.84 kg / kg supplement DM in early, mid, and late lactation, respectively ($P < 0.01$).

This effect of SOL is also evident in the Pasture DMI responses to supplementary feeding. Pasture DMI decreased (P = 0.06) with supplement DMI, but the effect was smaller in late lactation than in early and mid-lactation, which did not differ from each other: change in pasture DMI = -0.34, -0.30 and -0.17 kg DM per kg supplement eaten in early, mid, and late lactation, respectively.

Table 4.4: Average marginal dry matter intake (DMI) and milk production responses of grazing dairy cows, to supplement DMI at different stages of lactation. Results from a weighted analyses[1] of 26 studies conducted between 1985 and 2008, under a range of management conditions[2]

		Stage of lactation				
		Early	Mid	Late	SED[3]	*P*-value
DMI, kg DM/cow/d	Pasture	-0.34	-0.30	-0.17	0.051	< 0.05
	No. Studies	*9*	*8*	*5*		
	Total	-	-	-	-	-
	No. Studies	*0*	*0*	*0*		
Yield	Milk (kg/cow/d)	0.55	0.80	0.69	0.127	0.18
	No. Studies	*9*	*9*	*5*		
	4% FCM[4] (kg/cow/d)	0.59	0.48	0.84	0.120	< 0.05
	No. Studies	*4*	*3*	*1*		
	Fat (g/cow/d)	12.8	20.8	-	9.99	0.44
	No. Studies	*5*	*6*	*0*		
	Protein (g/cow/d)	26.2	32.7	-	4.66	0.21
	No. Studies	*5*	*7*	*0*		
	Milksolids (g/cow/d)	-	-	-	-	-
	No. Studies	*0*	*0*	*0*		
Milk Composition, %	Fat	-0.03	-0.04	-0.01	0.018	0.29
	No. Studies	*9*	*8*	*5*		
	Protein	0.01	0.02	0.02	0.007	0.58
	No. Studies	*9*	*8*	*4*		

[1] Analyses weighted by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies.
[3] Standard error of the difference
[4] 4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).

4.3 Effect of milk production and pasture DMI of the control group on milk production and pasture DMI responses to supplementary feeds

The level of pasture DMI and–milk production in the control group (i.e., the cows consuming pasture-only) influenced the magnitude of the milk production and pasture DMI responses to supplement. These results are presented in Table 4.5 and Table 4.6.

Non-weighted

When the amount of pasture consumed by the control group was included in the model, SOL no longer affected (P = 0.18) the association between supplement DMI and pasture DMI. The model including only pasture DMI (i.e., having removed SOL), had a slope of 0.03; for every kg increase in pasture DMI by cows in the control group, pasture DMI declined by a further 0.03 kg/kg supplement DMI in the treatment group. This means that as pasture DMI in the control treatment increased from 13 to 14 kg DM/d, the reduction in pasture DMI changed from 0.3 to 0.33 kg DM/d.

As with pasture DMI in the control group, SOL no longer affected the marginal response to supplement when 4% FCM, milk yield, milk fat yield, MS yield, and milk protein concentration of the control group of cows was included in the predictive model. The greater these milk production variables in the control group of cows, the smaller the milk production responses to supplement eaten:

- The milk yield response to supplement declined by 0.028 kg (28 ± 8 g) with each kg increase in milk yield in the control group; for example, as milk yield of the control cows increased from 18 kg to 19 kg, the increase in marginal milk declined from 0.65 to 0.61 kg/kg supplement DMI
- For every kg increase in 4% FCM yield in the control group of cows, the 4% FCM response to supplement eaten declined by 0.044 kg (44 g); this means that as 4% FCM yield in the control treatment increased from 19to 20 kg/d, the increase in 4% FCM yield changed from 0.64 to 0.60 kg/d.
- For each 100 g increase in milk fat yield in the control group of cows, the milk fat yield response to each 1 kg DM supplement declined by 4.6 ± 0.9 g; for example,

as milk fat yield of the control cows increased from 75 g to 175 g, the increase in marginal milk fat changed from 19.35 g to 14.75 g/kg supplement DMI;

- For every 0.1 kg increase in MS yield in the control group of cows, the MS yield response to each kg of supplement declined by 3.9 ± 0.8 g; for example as MS yield of the control cows increased from 1.3 g to 1.4 g, the increase in marginal MS changed from 44.8 g to 48.7 g/kg supplement DMI;
- The protein concentration response to each kg DM supplement declined by 0.0004 ± 0.0001% for every 0.1% increase in protein concentration in the control group of cows; for example as protein % of the control cows increased from 0.56 % to 0.66%, the increase in marginal protein % changed from 0.017 % to 0.013 %/kg supplement DMI;
- On average, the milk fat concentration response to supplement declined by 0.006 ± 0.0012 for every 0.1% increase in the milk fat concentration in the control group of cows. However, SOL modified and control group milk fat% interacted to affect the milk fat% response to supplementary feed DMI. The reduction in milk fat % associated with supplement DMI changed by -0.0008 in early lactation, 0.00009 in mid lactation and -0.0008 in late lactation.

Table 4.5: The effect of milk production and pasture DMI of the control group (unsupplemented group) on milk production and pasture DMI responses to supplementary feeds. Results are from a non-weighted analyses[1] of 83 treatments from 26 studies conducted between 1985 and 2008 and under a range of management conditions[2].

	Effect on the marginal response[3]	SE[4]	*P*-value
DMI, kg DM/cow/d			
Pasture DMI (kg DM/cow/d)	0.033	0.008	<0.001
Yield			
Milk (kg/cow/d)	-0.028	0.008	< 0.05
4% FCM[5] (kg/cow/d)	-0.044	0.008	<0.001
Fat (g/cow/d)	-0.046	0.009	<0.001
Protein (g/cow/d)	-0.015	0.009	0.112
Milksolids (g/cow/d)	-0.039	0.008	<0.001
Milk Composition			
Fat %	-0.055	0.013	<0.001
Protein %	-0.043	0.011	<0.001

[1] Analyses not weighted by the reciprocal of the standard error of the mean squared
2 See Appendix 1 for details of the actual studies.
[3] The effect of the control group variable on the marginal response to supplementary feed (for the same variable).
[4] 4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).
[5] Standard error

Weighted

In the weighted analysis, when pasture DMI in the control group was included in the model, the interaction between SOL and supplement DMI on pasture DMI also became non-significant. In contrast to the non-weighted analyses, however, as pasture DMI of the control group increased, the reduction in pasture DMI in response to supplementary feed intake got smaller; for every kg increase in pasture DM consumed by the control group, pasture DMI response to supplement declined by 0.04 ± 0.008 kg ($P < 0.001$). This means that the reduction in pasture DMI with each kg supplement DMI changed from 0.28 to 0.24, as pasture DMI of the control increased from 13 to 14 kg DMI/d.

The association between the unsupplemented milk yield, 4% FCM yield, and protein concentration of the control cows and the milk yield, 4% FCM yield, and protein concentration responses to supplement, respectively, were the same in the weighted and non-weighted analyses. However, there was an interaction between milk protein % in the control group, and SOL on the association between supplement DMI and milk protein %. For every 0.1% increase in milk protein % in the control group of cows, the increase in milk protein % associated with supplement DMI increased by 0.005 in early lactation, 0.006 in mid lactation, and 0.018 in late lactation (i.e., the increase in milk protein concentration response to supplement, mainly occurred in late lactation and was less obvious in early and mid-lactation).

Milk protein yield in the control group affected the milk protein yield response to supplement DMI in the weighted analyses ($P < 0.05$). For every 100 g increase in milk protein yield in the control group of cows, the protein yield response to supplement DMI decreased by 3.6 ± 1.53 g, irrespective of stage of lactation. This means that the increase in protein yield associated with each kg supplement DMI changed from 29.6 to 26.0, as protein yield of the control increased from to 0.56 to 0.66 kg/d.

The association between fat concentration in the control group and supplementary feed DMI on the milk fat concentration response to supplement was different to the association detected in the non-weighted analysis. Not only did the size of the effect differ, the direction of the response inverted and was positive in the weighted analysis. Associated with each 0.1% increase in milk fat concentration, the milk fat % response to supplement declined by 0.0004 ± 0.002 ($P < 0.05$). For example, as milk fat % of the control cows increased from 4.24 % to 4.34 %, the increase in marginal fat % changed from 0.027 %

to 0.023 %/kg supplement DMI. However, contrary to results in the non-weighted analysis, there was no significant effect of SOL on the association between control group milk fat % and the marginal milk fat % response to supplement.

Table 4.6: The effect of milk production and pasture DMI of the control group (unsupplemented group) on milk production and pasture DMI responses to supplementary feeds. Results are from a weighted analyses[1] of 72 treatments in 22 studies conducted between 1985 and 2008 and under a range of management conditions[2].

	Effect on the marginal response[3]	SE[4]	*P*-value
DM Intake			
Pasture DMI (kg DM/cow/d)	-0.037	0.008	<0.001
Milk Yield			
Milk (kg/cow/d)	-0.028	0.009	< 0.05
4% FCM (kg/cow/d)	-0.0446	0.014	< 0.05
Fat (g/cow/d)	-0.016	0.031	0.605
Protein (g/cow/d)	-0.036	0.015	< 0.05
Milksolids (g/cow/d)	-	-	-
Milk Composition			
Fat %	-0.041	0.019	< 0.05
Protein %	-0.037	0.012	< 0.05

[1] Analyses weighted by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies.
[3] The effect of the control group variable on the marginal response to supplementary feed (for the same variable).
[4] 4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).
[5] Standard error

There were no statistically significant effects of control group pasture DMI on the marginal response of any milk production or milk composition variables to supplement DMI in both the weighted and non-weighted analyses. This means that greater pasture DMI by the unsupplemented cows was not associated with a decrease in the milk production response to supplement, even though supplements reduced the pasture DMI in the non-weighted analysis.

4.4 **Association between supplementary feeding and post-grazing residual height and mass**

The changes in PGR height and mass when dairy cows grazing pasture are offered various supplementary feeds are presented in Table 4.7 and Table 4.8.

Non-weighted

The non-weighted analyses (Table 4.7) included 67 treatments and 19 studies. On average, marginal PGR height and mass increased 1.04 ± 0.1 mm and 42 ± 4.4 kg DM/ha for every additional kg supplement DM consumed ($P < 0.001$). This means that associated with every kg DM supplement consumed, PGR height and mass increased by 1.4 mm and 42 kg DM/ha.

Table 4.7: Average marginal post-grazing residual responses to supplement DMI in grazing dairy cows from a non-weighted analyses[1] of 67 treatments in 19 studies conducted between 1985 and 2008, under a range of management conditions[2].

	Marginal Response	SE[3]	No. Studies	No. Treatments	*P*-value
Post-grazing Residual					
Post-grazing mass (kg DM/ha)	41.9	4.40	19	67	< 0.001
Post-grazing height (mm)	1.0	0.12	12	40	< 0.001

[1] Analyses not-weighted by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies
[3] Standard error

Weighted

In the weighted analyses, which included 42 treatments from 14 studies (Table 4.8), the increase in PGR height in response to supplement DMI was the same as in the non-weighted analyses. However, the weighted PGR mass response to supplement, which excluded 5 studies and 25 treatments, was greater: 60 ± 7.4 kg DM/ha per kg supplement DMI (P <0.001).

Table 4.8: Average marginal post-grazing residual responses to supplement DMI in grazing dairy cows from a weighted analyses[1] of 42 treatments in 14 studies conducted between 1995 and 2008, under a range of management conditions[2]

	Marginal Response	SE[3]	No. Studies	No. Treatments	*P*-value
Post-grazing Residual					
Post-grazing mass (kg DM/ha)	59.8	7.36	14	42	< 0.001
Post-grazing height (mm)	1.1	0.14	7	25	< 0.001

[1] Analyses weighted by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies
[3] Standard error

4.5 Average marginal post-grazing residual responses to supplementary feeds at different stages of lactation

The PGR height and mass response to supplementary feeding were affected by stage of lactation in the weighted analysis, but not in the non-weighted analysis. These effects are presented in Table 4.9 and Table 4.10.

The results from the analysis indicate that the greatest marginal response to supplement on the PGR height was evident in early lactation, followed by mid-, and then late lactation. The marginal PGR height response was 1.7, 0.9, and 0.4 ± 0.4 mm increase in pasture height for every 1 kg increase in supplement DMI in early, mid, and late lactation. This means that if a cow consumed 3 kg DM of supplement in early, mid, or late lactation, post-grazing residual height increased by 5.1, 2.7, and 1.2 mm, respectively. Stage of lactation did not have a significant effect on the PGR mass response to supplement in neither the weighted ($P = 0.38$) nor the non-weighted ($P = 0.58$) analyses.

Table 4.9: Average marginal post-grazing residual responses to supplement DMI at different stages of lactation. Results from a non-weighted analyses[1] of 19 studies conducted between 1985 and 2008, under a range of management conditions[2].

	Stage of lactation				
	Early	Mid	Late	SED[3]	*P*-value
Post-grazing Residual					
Post-grazing mass (kg DM/ha)	46.95	49.00	37.11	13.89	0.58
No. Studies	*5*	*9*	*7*		
Post-grazing height (mm)	1.9	1.3	0.9	0.41	0.10
No. Studies	*4*	*5*	*5*		

[1] Analyses not weighted by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies
[3] Standard error of the difference

Table 4.10: Average marginal post-grazing residual responses to supplement DMI at different stages of lactation. Results from a weighted analyses[1] of 19 studies conducted between 1985 and 2008, under a range of management conditions[2].

	Stage of lactation				
	Early	Mid	Late	SED[3]	*P*-value
Post-grazing Residual					
Post-grazing mass (kg DM/ha)	59.16	62.77	40.29	18.3	0.38
No. Studies	*4*	*5*	*4*		
Post-grazing height (mm)	1.7	0.9	0.4	0.39	< 0.05
No. Studies	*4*	*3*	*2*		

[1] Analyses weighted by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies.
[3] Standard error of the difference

4.6 Association between pasture DMI of the control group and the post-grazing residual responses to supplement

There was no statistically significant association between control group pasture DMI on any PGR responses to supplement. This means that greater pasture DMI's by the unsupplemented cows were not associated with a change in the PGR height and mass responses to supplement.

4.7 Interaction between the post-grazing residual pasture height and mass in the control group and the change in post-grazing residual height and mass in response to supplement

Non-weighted

When the PGR mass by the control group was included in the model, SOL still had no affect ($P = 0.17$) on the association between supplement DMI and PGR mass. The model with only PGR mass of the control group (i.e., having removed SOL), had a slope of 0.017; this means that for each 100 kg DM/ha increase in PGR mass in the control group of cows, the increase in PGR mass associated with increasing supplement DMI increased by 1.7 ± 0.8 kg DM/ha, irrespective of stage of lactation ($P < 0.01$). This means that the greater the PGR mass of the unsupplemented group, the greater the increase in pasture residual mass when cows consume supplementary feeds. However, the PGR height of the control group was not associated with the PGR height response to supplement ($P = 0.18$) at any stage of lactation.

Table 4.11: The effect of the post-grazing residual of the control group (unsupplemented group) on post-grazing residual responses to supplementary feeds. Results are from a non-weighted analyses[1] of 67 treatments in 19 studies conducted between 1985 and 2008, under a range of management conditions[2].

	Effect on the marginal response[3]	SE[4]	*P*-value
Post- Grazing Residual			
Post-grazing mass (kg DM/ha)	0.017	0.0078	< 0.05
Post-grazing height (mm)	0.011	0.0077	0.18

[1] Analyses not weighted by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies.
[3] The effect of the control group variable on the marginal response (for the same variable) to supplementary feed
[4] 4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).
[5] Standard error

Weighted

The effect of unsupplemented PGR mass on the increase in the PGR mass associated with supplementary feeding, was greater in the weighted analysis (Table 4.12). For every 100 kg DM/ha increase in PGR mass by the control group of cows, the PGR mass response to supplement DMI increased by 2.6 ± 0.98 kg DM/ha. However, this effect was dependent on SOL (interaction: $P < 0.05$). For every 100 kg DM/ha increase in PGR mass in the control treatment, the increase in PGR mass associated with supplement DMI increased by 1.0 kg DM/ha in early lactation, 8.2 kg DM/ha in mid lactation, and 3.2 kg DM/ha in late lactation.

On average, the PGR height of the control group was not associated with the PGR height response to supplement DMI ($P = 0.60$). There was, however, an interaction ($P < 0.05$) between SOL and unsupplemented post-grazing height. For every 10 mm increase in PGR height in the control group of cows, the increase in PGR height associated with supplement DMI increased by 0.22 mm in early lactation, 1.50 mm in mid lactation, 0.46 mm in late lactation.

Table 4.12: The effect of the post-grazing residual of the control group (unsupplemented group) on post-grazing residual responses to supplementary feeds. Results are from a weighted analyses[1] of 42 treatments in 14 studies conducted between 1995 and 2008, under a range of management conditions[2]

	Effect on the marginal response[3]	SE[4]	*P*-value
Post- Grazing Residual			
Post-grazing mass (kg DM/ha)	0.026	0.0098	< 0.05
Post-grazing height (mm)	0.004	0.0081	0.597

[1] Analyses weighted by the reciprocal of the standard error of the mean squared
[2] See Appendix 1 for details of the actual studies.
[3] The effect of the control group variable on the marginal response (for the same variable) to supplementary feed
[4] 4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).
[5] Standard error of the mean

4.8 Association between unsupplemented post-grazing residual and the pasture DMI and milk production responses to supplement

In the analysis of the effect of the pasture PGR of the control group of cows, on the milk production responses to supplementary feed, SOL was always included in the model. This is because a change in the milk production responses to supplementary feed could not feasibly be associated with the PGR of the control group, when SOL is not taken into account. Pasture PGR in the control group (i.e., receiving no supplement) affected some of the milk production and pasture DMI responses to supplement. These results are presented in Table 4.13 and Table 14.4.

Non-weighted

For each 100 kg DM/ha increase in post-grazing pasture mass in the control group of cows, the pasture DMI response to supplementary feeding declined by 0.013 ± 0.0046 kg (13 ± 4.6 g; $P < 0.01$). This means that the SbR decreased by 13 g/kg supplement DMI

Though the PGR height of the control group did not influence the average marginal

production responses to supplement DMI, on average, there was a significant interaction between SOL and unsupplemented PGR height on the milk protein yield response ($P < 0.05$). Associated with a 10 mm increase in PGR height in the control group of cows, was a change in the protein yield response to supplement DMI of -20.9 g in early lactation, 15.6 g in mid lactation and -29.4 g in late lactation.

The PGR mass of the control group affected average marginal milk yield response ($P < 0.05$). With each 100 kg DM/ha increase in PGR mass of the control group of cows, the milk yield response to supplement decreased by 0.02 ± 0.008 kg (20 ± 8 g). For example, a PGR mass increase from 1500 to 1600 kg DM/ha in the control group of cows was associated with a change in the marginal milk yield response to supplement from 0.60 to 0.58 kg milk/kg supplement DMI.

Table 4.13: The effect of the post-grazing residual of the control group (unsupplemented group) on pasture dry matter intake and milk production responses to supplementary feeds. Results are from a non-weighted analyses[1] of 67 treatments in 19 studies conducted between 1985 and 2008, under a range of management conditions[2].

	Post-grazing mass of the control group		
	Effect on the marginal response[3]	SE[4]	*P*-Value
DM Intake			
Pasture DMI (kg DM/cow/d)	-0.00013	0.00004559	< 0.05
Milk Yield Response			
Milk (kg/cow/d)	-0.00017	0.000077	< 0.05
4% FCM[5] (kg/cow/d)	-0.00011	0.000081	0.194
Fat (g/cow/d)	-0.00106	0.003670	0.775
Protein (g/cow/d)	-0.00499	0.002542	0.057
Milksolids (g/cow/d)	-0.00565	0.006030	0.355
Milk Composition			
Fat %	0.00001	0.000012	0.416
Protein %	0.00001	0.000006	0.256

	Post-grazing height of the control group		
	Effect on the marginal response	SE	*P*-value
DM Intake			
Pasture DMI (kg DM/cow/d)	-0.0355	0.016417	< 0.05
Milk Yield Response			
Milk (kg/cow/d)	-0.04422	-0.04422	0.121
4% FCM (kg/cow/d)	-0.04296	0.026721	0.118
Fat (g/cow/d)	-1.359	1.2984	0.309
Protein (g/cow/d)	-1.512	1.0055	0.153
Milksolids (g/cow/d)	-2.356	1.9971	0.249
Milk Composition			
Fat %	-0.003	0.0038644	0.453
Protein %	-0.000409	0.00178237	0.82

[1] Analyses not weighted by the reciprocal of the standard error of the mean squared

[2] See Appendix 1 for details of the actual studies.

[3] The effect of the control group variable on the marginal response to supplementary feed (for the same variable).

[4] Standard error

[5] 4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).

Weighted

The effect of PGR mass on pasture DMI responses to supplementary feed, was smaller and positive in the weighted analyses. This means that that the reduction in pasture DMI response increased (i.e., the SbR increased). For every 100 kg DM increase in PGR mass, the SbR increased by 0.01 ± 0.004 g ($P < 0.01$).

Associated with every 10 mm increase in PGR height in the control treatment, 4% FCM response declined ($P < 0.05$) 45 ± 16.3 g, the milk yield response declined ($P < 0.05$) 55 ± 21.6 g, milk fat yield response declined ($P < 0.05$) 44.3 ± 13.35 g, and the milk protein yield response declined ($P = 0.06$) 28.9 ± 12.73 g.

Though the PGR height of the control group did not influence the average marginal milk fat concentration response to supplement DMI on average ($P = 0.40$), there was a significant interaction between SOL and unsupplemented PGR height ($P < 0.05$). Associated with every 10 mm increase in PGR height in the control group of cows, the decline in the fat % response to supplement DMI was of 0.003 % in early lactation, 0.0001 % in mid lactation, and 0.044 % late lactation.

The PGR mass of the control group affected the average milk yield ($P < 0.05$), 4% FCM yield ($P = 0.06$), protein yield ($P < 0.05$), and milkfat % ($P < 0.05$) responses to supplement DMI. A 100 kg DM/ha increase in PGR pasture mass in the control treatment, was associated with the response in milk, 4% FCM, and milk protein yield responses to supplement decreasing by 0.02 ± 0.007 kg (20 ± 7.2 g), 0.14 ± 0.006 kg (13.6 ± 6.2 g), and 0.0013 ± 0.00034 kg (1.3 ± 0.34 g), while the milk fat % response to supplement DMI increased ($P < 0.05$) by 0.0024 ± 0.0011 %. This means that the reduction in milk fat% in response to supplement DMI, became smaller when PGR mass of the control group increased by 100 kg DM/ha.

Table 4.14: The effect of the post-grazing residual of the control group (unsupplemented group) on pasture dry matter intake and milk production responses to supplementary feeds. Results are from a weighted analyses[1] of 42 treatments in 14 studies conducted between 1995 and 2008, under a range of management conditions[2]

	Post-grazing mass of the control group		
	Effect on the marginal response[3]	SE[4]	*P*-Value
DM Intake			
Pasture DMI (kg DM/cow/d)	0.000144	0.000040	< 0.05
Milk Yield			
Milk (kg/cow/d)	-0.000175	0.071630	< 0.05
4% FCM[5] (kg/cow/d)	-0.000136	0.011540	0.055
Fat (g/cow/d)	-0.001548	0.011593	0.898
Protein (g/cow/d)	-0.013350	0.003400	< 0.05
Milksolids (g/cow/d)	-		-
Milk Composition			
Fat %	0.000024	0.000011	< 0.05
Protein %	0.000005	0.000007167	0.505

	Post-grazing height of the control group		
	Effect on the marginal response	SE	P-value
DM Intake			
Pasture DMI (kg DM/cow/d)	0.006784	0.0178386	0.708
Milk Yield			
Milk (kg/cow/d)	-0.05547	0.021674	< 0.05
4% FCM (kg/cow/d)	-0.04518	0.016322	< 0.05
Fat (g/cow/d)	-4.431	1.3348	< 0.05
Protein (g/cow/d)	-2.888	1.2726	0.056
Milksolids (g/cow/d)	-	-	-
Milk Composition			
Fat %	0.002472	0.0028163	0.398
Protein %	0.000573	0.0012893	0.66

1 Analyses weighted by the reciprocal of the standard error of the mean squared

2 See Appendix 1 for details of the actual studies.

3 The effect of the control group variable on the marginal response to supplementary feed (for the same variable).

4 Standard error

5 4% fat-corrected milk ([(0.4 × kg of milk) + (15.0 x kg of fat)]).

Chapter 5 Discussion

5.1 Thesis novelty and main results

Although milk production responses to supplementary feeds in grazing systems is a well-published topic, the research contained in this thesis is novel because the size of the collated database is larger than in previously-published analyses, it includes more recent studies, and it is the first, I believe, that examines the association between pasture-related variables and responses to supplements.

Based on the analyses undertaken, I conclude that offering grazing dairy cows supplementary feeds increases total DMI, but leads to a reduction in pasture DMI (i.e., cows substituted the supplementary feed for pasture). As a result of the increase in total DMI, milk production increased; however, pasture utilisation declined due to the reduction in pasture DMI and this was evidenced by an increase in residual height or mass. Effects of PGR height and pasture DMI at zero supplementary feed intake (i.e., unsupplemented group in experiment) on the PGR and pasture DMI responses to supplementary feed, however, were inconsistent. The significance of these results will be discussed in this section.

The results of the both the weighted and non-weighted analyses have both been presented; though, statistically, the results of the non-weighted analysis are less robust. However, I've chosen to present them because the number of studies in the dataset is significantly reduced when only those reporting SE's are included, especially for the analyses of the pasture variables. This significant drop in study numbers in the weighted analyses, because of the lack of reporting on standard errors has been recognised as a limitation, and the results from these analyses are interpreted with caution.

5.2 Associations among supplementary feed use and pasture-level variables

5.2.1 Associations between supplementary feed DMI, substitution rate, and post-grazing residual height and mass

On average, offering grazing dairy cows supplementary feeds increased total DMI, but by less than the total amount of supplement DMI. This is because pasture DMI declined linearly with increasing supplement DMI, a phenomenon known as the substitution of supplementary feeds for pasture. The SbR is the size of the reduction in pasture DMI relative to the amount of supplement consumed. For example, if pasture DMI declined by 1 kg DM when 3 kg DM of supplement was consumed, SbR was 33% (1 ÷ 3); if pasture DMI declined by 1.5 kg DM, SbR was 50% (1.5 ÷ 3). In my data, on average, pasture DMI declined by 0.28 kg DM/cow/d with every 1 kg supplement DM consumed. Therefore, SbR was, on average, 28% (non-weighted analyses = 30%).

These results mean that, on average, the utilisation of pasture declined when cows consumed supplementary feeds. Consistent with the linear decline in pasture DMI with increasing supplement, offering grazing dairy cows supplementary feeds was associated with increases in both the PGR mass and height (in both the weighted and non-weighted analyses). On average, the marginal PGR height and mass increased by 1.0 mm (both analyses) and 42 (non-weighted) to 60.7 (weighted) kg DM/ha respectively, for every 1 kg supplement DM consumed/cow. As the increase in PGR with supplementary feeding is a result of substitution, it's expected that the factors that affect the SbR, will also affect the magnitude of the PGR response.

The reduction in pasture DMI when cows consume supplementary feeds has been well established. As early as 1968, results from research experiments indicated that the feeding of supplements to grazing dairy cows reduced pasture DMI (Leaver et al., 1968) and, since then, substitution has been a well-researched topic (Bargo et al., 2003; Stockdale, 2000b). Though the magnitude of the reported SbR is variable, the SbR of 28%, from my analyses, is similar to the average SbR reported by Penno (2002; 31% from a review of 17 feeding experiments published between 1984 and 1998), Thomas (1987; 52% from a review of 27 experiments), and, more recently, one study in New Zealand (Higgs et al., 2011; 30%).

The reason for the reduction in pasture DMI when a supplementary feed is consumed cannot be stated, with certainty, but it has been hypothesised that the effect is a result of complex neuroendocrine factors centrally regulated in the hypothalamus and brainstem (Roche et al., 2008). When grazing dairy cows consume supplementary feeds, time spent grazing declines by around 12 minutes per kilogram of supplement (Bargo et al., 2003; Sheahan et al., 2011). This decline in time spent grazing indicates that the cow has reached satiety earlier than if it had not consumed the supplementary feed. Support for this was presented in a manuscript by (Roche et al., 2007), where they measured the concentrations of circulating blood ghrelin (a hunger-signalling hormone produced primarily in the stomach of monogastrics and the abomasum of ruminants as a signal of nutritional status, in particular) and insulin (a pancreatic hormone that regulates the storage and use of glucose and fat) in cows that had been fed varying levels of supplement. They reported that as the level of supplement DMI increased, concentrations of ghrelin declined linearly while insulin increased; these results support the hypothesis that supplementation resulted in a neuroendocrine signal to cease eating, which resulted in cows whose hunger was satisfied earlier compared with cows that weren't supplemented. The effect of supplementation on the hormones ghrelin and insulin, and resultant effect on pasture DMI is presented in Figure 5.1.

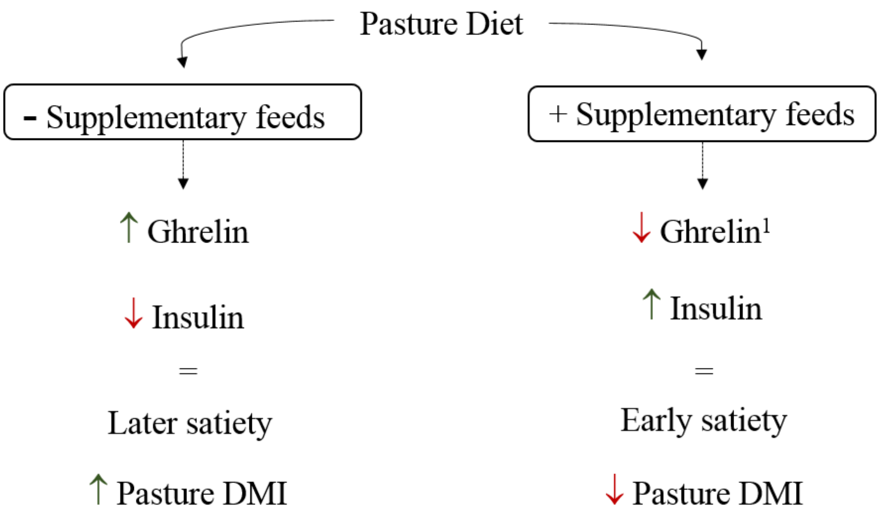

Figure 5.1: Simplified model to depict the effect of supplementary feed on neuroendocrine factors and the impact this has on pasture DMI. Adapted from Seeley and Schwartz (1997).

Although physical factors can also cause the cow to reduce their grazing time, as rumen fill limits intake, this, primarily, only happens to cows grazing low digestibility forages (van Soest, 1994) and is unlikely to be a factor on highly digestible ryegrass-white clover pastures, except, maybe, in summer. When we examine the reduction in pasture eaten relative to concentrate consumed on a mass or volume basis, the argument against physical fill being a contributing factor is even more compelling. My results indicate that cows reduce their DMI of pasture by 0.28 kg DM for every 1 kg DM of a concentrate feed eaten. This is the equivalent to a cow refusing 1.9 kg fresh weight of pasture (i.e., 0.28 kg DM at an average of 15% DM) when they consume 1.1 kg fresh weight of a concentrate feed (i.e., 1 kg DM concentrate at an average of 90% DM). From a volume perspective, 1 t DM of compressed pasture (i.e., as measured in a silage stack) is 6 to 8 m^3 (depending on moisture content; DairyNZ, 2016). This means that 1 kg DM pasture occupies approximately 8 L of volume (assuming 85% moisture content). In comparison, a grain like barley has a bulk density of approximately 620 kg DM/m^3 (which is 570 kg DM/m^3 or 0.6 kg DM/L; Engineering Toolbox, 2001); therefore, 2 kg DM occupies only 3.3 L or 36% of the volume of the pasture refused. In our example, therefore, cows reduced the pasture mass consumed by 3.8 kg and the pasture volume consumed by 4 to 5 L when offered 2.2 kg (fresh) or 3.3 L of a concentrate supplement. The reduction in the amount of fresh material eaten when supplements were consumed refutes the premise that physical factors limit DMI in grazing dairy cows or, at least, indicate that they are not the primary driver of SbR in supplemented grazing dairy cows (Roche et al., 2008).

In reality, voluntary feed intake is complex and is regulated by both neuroendocrine and physical factors (Forbes, 1988; van Soest, 1994). However, in the dairy cow grazing highly digestible pastures, physical factors have very little effect on DMI (Vazquez & Smith, 2000) and neuroendocrine factors most affect DMI and SbR (Roche et al., 2008).These neuroendocrine signals are affected by other factors that have been reported to affect DMI (e.g., stage of lactation; Roche et al., 2008). My results also indicate that multiple factors influence SbR. These will be discussed further.

5.2.2 Associations among the relative feed deficit and the substitution rate and post-grazing residual height and mass responses to supplements

Pasture DMI and PGR height or mass at zero supplement intake is reflective of the RFD of the herd (i.e., when pasture DMI and pasture residual of the control group is less, the RFD is likely to be greater). The pasture DMI and PGR height and mass of the cows in the control treatment in the studies included in my analyses affected the size of the SbR when grazing dairy cows consumed supplementary feeds. However, the association among pasture DMI, PGR of the control group (i.e. the RFD), and SbR and PGR height and mass responses to supplement were not consistent.

In the non-weighted analysis, for every 1 kg increase in pasture DMI of cows in the control group, there was a 3 percentage point (11%) increase in SbR. This means that if unsupplemented cows were eating 13 kg pasture DM, they would refuse 0.56 kg DM of pasture if they consumed 2 kg DM of a concentrate supplement; however, if they had been consuming 14 kg pasture DM, they would refuse 0.62 kg pasture DM following the consumption of 2 kg DM supplementary feeds. This is consistent with previous studies (Rogers, 1985; Stockdale et al.,1997; Stockdale, 2000), who reported that as pasture DMI increased, the amount of pasture refused when cows consumed a supplementary feed increased. In agreement with these results, Grainger and Mathews, (1989), reported a highly significant linear relationship between unsupplemented pasture DMI and SbR, from their experiments and other published data (Figure 5.2).

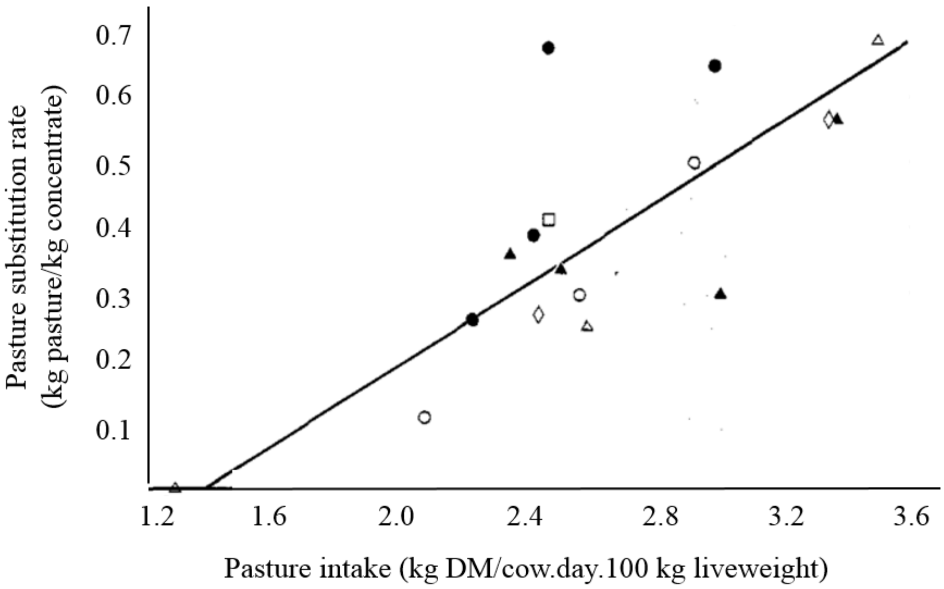

Figure 5.2: Effect of pasture intake at zero concentrate intake (Pasture Intake; kg DM/cow.day/100 kg liveweight) on the pasture substitution rate of cows offered concentrates for Grainger and Matthews 1989 (Δ), Meijs and Hoekstra 1984 (○), Stockdale and Trigg 1985 (□), Stakelum a (◊), 1986b (▲), 1986c (●). The equation of the line is: SbR = -0.445 + 0.315 (± 0.057)PI (Variance accounted for = 63.5%; r.s.d = 0.129; c.v. = 34.7%; n=18; Grainger & Matthews, 1989).

The increase in SbR as pasture DMI of the control group increased (in the non-weighted analyses) is also consistent with the concept of a RFD. The RFD is the ability of the diet to satisfy the cow's nutrient requirements relative to the requirements of that cow for its potential production level (Leaver, 1986; Mayne, 1991; Penno, 2002). In simpler terms, it is how 'hungry' the cow is before any additional feed is provided. Data from multiple experiments in grazing systems (76 data sets) were collated to identify the key variables affecting SbR when concentrate supplements were fed (Stockdale, 2000b). These analyses highlight the significance of pasture DMI of the control group (i.e., RFD) on

SbR. In the results from Stockdale (2000), SbR increased by 0.21 kg pasture DM/kg DM concentrate increase for each additional kg DM of pasture/100 kg live weight in the unsupplemented diet. This means that for a 500 kg cow, pasture DMI declined by an additional 0.04 kg DM/kg supplement DM consumed for every 1 kg DM increase in pasture DMI. In other words, SbR increased by 0.04 (i.e., by 4 percentage points, or from 28% to 32%, for example). This is almost identical to the results of the non-weighted analysis presented here. Put simply, the less hungry a cow is prior to the provision of supplement (i.e., the smaller the RFD), the higher the SbR.

The weighted analyses, however, reflect contradictory results. The reduction in pasture DMI in response to supplementary feed intake got smaller; for every kg increase in pasture DM consumed by the control group, the pasture DMI response to supplement declined by 0.04 kg. This means that the reduction in pasture DMI with each kg supplement DMI changed from 0.28 to 0.24, as pasture DMI of the control increased from 13 to 14 kg DMI/d. This effect is hard to explain and contradicts the majority of 'intervention-approach' experiments and is not consistent with what is known about the neuroendocrine regulation of hunger, satiety, and, consequentially, intake (Roche et al., 2008). The effect may be a consequence of inadequate sample size in the weighted analysis, a result of poor reporting of pasture-level variables in nutrition experiments for grazing systems. Nevertheless, the consistent results from 'interventionist-approach' experiments supersede the results of association analyses and our results highlight the risk of relying on association analyses and inductive reasoning, alone.

The PGR of unsupplemented cows is directly affected by their pasture allowance (Wales et al., 1998), which is the primary factor regulating DMI. In other words, the PGR of the unsupplemented cows should be reflective of the extent of the RFD. In my data, for every 100 kg DM/ha increase in PGR mass in the unsupplemented group of cows, the increase in PGR mass associated with supplementary feeding increased by a further 2.6 ± 0.98 kg DM/ha (1.7 ± 0.78 kg DM/ha in the non-weighted analysis; i.e., if the unsupplemented cows left pasture ungrazed, supplemented cows left even more behind). This result implies that as the PGR mass of the control group increased, SbR also increased when supplementary feeds are offered; this results in greater PGR's in supplemented herds.

As previously discussed, SbR increases as the RFD of the herd becomes smaller, resulting in more pasture being left ungrazed. Unsupplemented pasture DMI is the main determinant of the RFD, and maximum DMI is generally not achieved until about 50% of the total pasture offered is left ungrazed (Combellas and Hodgson, 1979). It has been hypothesised (Roche & White, 2012; Roche, 2017) that the PGR may be used as a ‘proxy’ measure for pasture DMI and thus the RFD. Although my results linking PGR mass in the unsupplemented group to an increase in PGR mass in the supplemented group supports a positive association between unsupplemented pasture DMI and the PGR mass and height responses to supplement DMI, the association between unsupplemented pasture DMI and SbR was not, however, consistent in my dataset. Furthermore the PGR height of the control group was not associated with the PGR height response to supplement DMI in neither the weighted nor the non-weighted analyses. The lack of consistent/significant effects may be real and the hypothesis is not correct, or it could be a function of the associative (rather than controlled experimentation) nature of the study or, potentially, it could be because the measurement of pasture DMI is by indirect methods (e.g., herbage disappearance, indigestible markers), increasing between-animal variability and reducing the likelihood of detecting a significant difference. Nevertheless, the bulk of the controlled experiments investigating the effect of supplementing grazing dairy cows has identified the pasture DMI of the unsupplemented group as a key factor explaining more than 30% of the variation in SbR.

In support of the hypothesis that PGR’s are indicative of the RFD, the PGR of the cows in the unsupplemented (control) group affected the size of the SbR when grazing dairy cows consumed supplementary feeds, in the weighted analysis. For every 100 kg DM/ha increase in control group PGR mass, the pasture DMI response increased by a 0.014 kg/kg supplement DMI (14 g/kg supplement DMI). This means that the SbR increased from 0.28% to 0.29%. This is consistent with the association between PGR height and the pasture DMI response to supplementary feeds, where pasture DMI further decreased (i.e., SbR increased) in response to supplementary feed as PGR height in the unsupplemented cows increased. Again, however, the non-weighted analysis indicated contradictory results and the same increase in unsupplemented PGR mass resulted in an equivalent reduction in the pasture DMI response of 0.013 kg/kg supplement DMI (13 g/kg supplement DMI decrease in SbR). Although we cannot determine with any certainty the reason for this inconsistency, it may reflect the lack of experiments and treatments that adequately report pasture-level variables.

5.3 Associations among supplementary feed use and milk production variables

5.3.1 Milk yield

On average, offering grazing dairy cows supplementary feeds increased milk production. The increase is due to the increase in total DMI that I reported earlier when supplements are fed (Beever & Thorp, 1997; Bargo et al., 2003; Roche, et al., 2013). In my data, on average, each 1 kg DM of supplementary feed consumed resulted in an additional 0.65 kg milk, 0.64 kg 4% FCM, 20 g milk fat, 30 g milk protein, (i.e., the equivalent of 50 g MS, although this couldn't be deduced statistically from the weighted analysis). These marginal responses are similar to those reported by Penno, (2002) who summarised 39 experiments published between 1979 and 1998. On average, for every 1 kg DM of supplement consumed, cows produced an additional 0.68 kg milk, 23 g milk fat and 20 g milk protein. However, they are smaller than those reported in reviews by Stockdale (2000) and Bargo et al., (2003), who both reported a MR of 1 kg milk / kg concentrate DM eaten.

Nutrient intake is the biggest limitation to milk production by grazing dairy cows (Leaver, 1985; McGilloway & Mayne, 1996). For example, Kolver and Muller (1998) demonstrated that more than 60% of the difference in MS production between a cow that consumes a TMR and cows grazing high quality pasture, can be accounted for by the difference in DMI. As feeding supplements resulted in an increase in DMI of 0.7 kg, on average, it resulted in an increase in milk production.

In theory, an additional kg of supplement containing 12.0 MJ ME/kg DM should produce up to 2.4 kg additional milk (Moran & McDonald, 2010); but, the reduction in pasture DMI, (i.e., substitution) and the partitioning of nutrients towards body reserves, not to mention a negative effect of starch consumption on the ME extracted from pasture (Doyle et al., 2005) results in smaller overall effects (Leaver et al., 1968; Leaver, 1986; Stockdale et al., 1997; Figure 5.3).

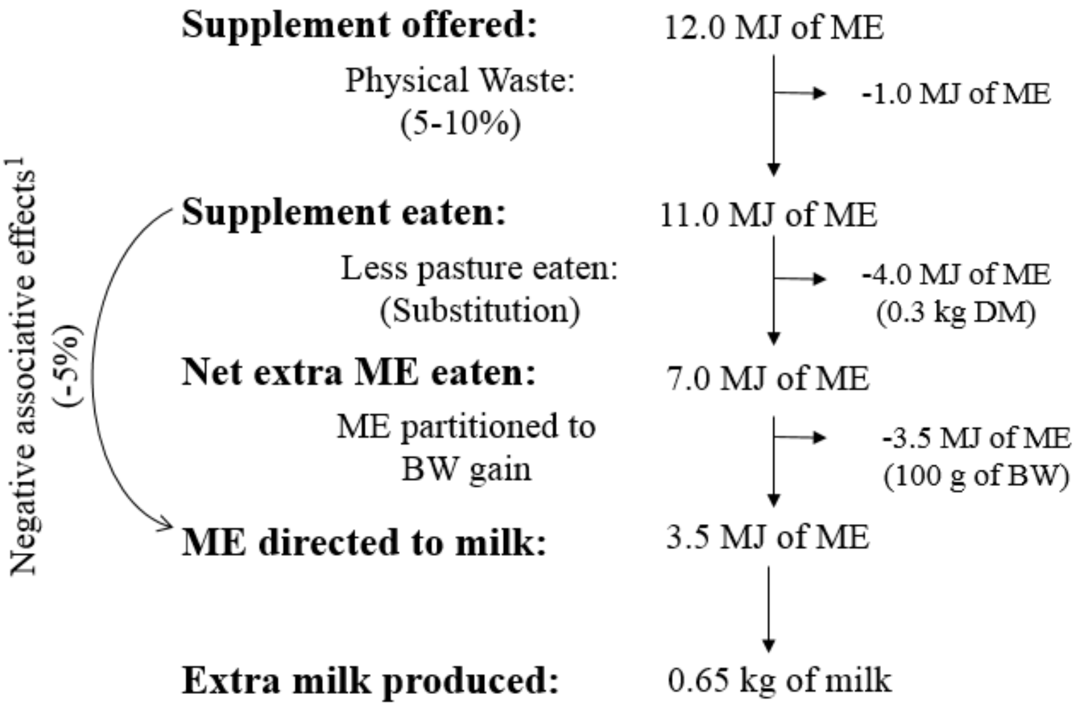

Figure 5.3: Schematic to depict the short-term response to 1 kg of high-quality supplement DM offered/cow. Source: Adapted from Holmes and Roche (2007). [1]Effect of grain supplements on the NDF digestibility of pasture (Doyle et al., 2005).

5.3.2 Milk composition

On average, offering grazing dairy cows supplementary feeds increased the protein content of the milk and decreased the fat content. For every kg supplement DMI, milk fat percent decreased by 0.03 to 0.04 percentage points and milk protein concentration increased by 0.02 percentage points. Therefore, the decrease in milk fat % was almost double the increase in milk protein %.

In support of these results, previous studies in pasture-based systems (Petch et al., 1997; Sayers, 1999; Reis & Combs, 2000) have indicated that supplementation with concentrate feeds linearly increases milk protein concentration. Increasing the concentrate intake from 5 to 10 kg DM/day increased milk protein from 3.37 to 3.55% (Sayers, 1999). This equates to an approximately 0.035 percentage point increase per kg supplement DM. Reis and Combs (2000) reported effects similar to my results; milk protein % increased from 2.85 to 2.95 as starch-based supplement DMI increased from 0 to 5 kg/day (0.02 percentage point increase per kg supplement DM). The reduction in milk fat % in my results, is also in agreement with these (and other) studies. Reis and Combs (2000) and Delaby et al., (2001) and more recently Higgs et al., (2013) indicated a linear decrease in milk fat % as supplement DMI increased. Sayers (1999) reported a decline in milk fat % from 3.66 to 2.99% when supplementation of cows grazing ryegrass pastures was increased from 5 to 10 kg/day; this is equivalent to 0.13% milk fat reduction with each additional kg supplement. Therefore, my results for the association between supplementary feeds and milk composition are consistent with those reported in the literature.

The decrease in milk fat and the increase in milk protein concentrations can, probably, be explained by the changing products of rumen fermentation (i.e., volatile fatty acids; VFAs) when supplementary feeds are consumed (Broderick, 2003). When starch is eaten, less acetate is produced from the rumen and more propionate is produced (Bauman et al., 1971; van Soest, 1994). The uptake of propionate from the rumen causes levels of circulating insulin to increase, which stimulates amino acid uptake by the mammary gland from the blood (Rius et al., 2010). The synthesis of milk fat, however, requires acetate. Thus, the feeding of starch-based supplements (e.g. cereal grains) will generally increase milk protein % and decrease milk fat %; in comparison, feeding pasture, or fibre-based supplements (e.g. palm kernel expeller, pasture silage) favours increased milk fat % and reduced milk protein % (Griinari et al., 1997; Rius et al., 2010). As well as changing the products of rumen fermentation, many reviews conclude that the increasing ME intake as supplements are fed, contributes to increases in milk protein % (Ettala, 1976; Rook & Thomas, 1980; Sporndly, 1989). Though my data contained both fibre- and starch-based supplementary feeds, the majority were starch-based, and thus support the literature for the effect of starch-based supplements on milk composition.

Changing milk composition to increase milk protein is a common incentive for farmers to use supplementary feeds (i.e., increase the protein to fat ratio), since, historically, in NZ milk pricing systems, milk protein was approximately twice the value milk fat (Fonterra, 2018), therefore, increasing milk protein is likely to increase the value of the milk. However, in my results, the decrease in milk fat% was double the increase in protein %; therefore, based on my data, the value of each L of milk wouldn't change, despite the milk composition changes.

Therefore, the only change to revenue would be through the increase in milk production, which was substantially lower than reported by Stockdale (2000) and Bargo et al., (2003). The response, however, is very similar to the response reported by Ramsbottom et al., (2015) on commercial dairy farms in Ireland. They also reported that the milk production response to supplements on farm was substantially lower than in the aforementioned reviews and concluded that the linear decline in pasture utilisation with supplementation resulted in the lower actual response to supplement than previously reported. Furthermore, the actual average MR to supplement in the 35 studies outlined in the summary table by Bargo et al., (2003) was 0.75 kg milk/kg supplement DMI and not the 1.0 kg reported in the abstract and conclusions. I do not know the reason for the discrepancy between what was reported in text and the calculated average from the studies reported in tables, but my results are similar to both Penno, (2002) and Ramsbottom et al., (2015) and indicate that the marginal milk production response to supplements is much lower than previously thought (0.65 kg milk and 30 and 20g of milk fat and milk protein, respectively).

5.3.3 The association between milk production and pasture DMI in the unsupplemented cows (control group) and the milk production responses to supplement

The level of milk production/cow in the control group (i.e., prior to consuming supplementary feeds) influences the marginal response to supplement DMI. As the milk production of the control group increased, the milk production responses to supplement decreased. In my data, for every kg increase in control group milk, 4% FCM, and milk protein yields, the average marginal responses to DMI decreased by 28, 44 and 30.6 g, respectively. Within the experiments analysed, total ME intake increased with additional DMI (either supplement or pasture). The results of an analyses of experiments by Penno (2002), who compared milk production responses to supplementary feeds of cows with different pre-treatment yields, supports my results. The largest marginal FCM response to increased ME intake was associated with cows with pre-treatment FCM yields 40% below their potential FCM yield, and the smallest marginal responses were associated with pre-treatment FCM yields 25% below their potential FCM yield.

The effect of unsupplemented milk yields on the response may, like the SbR, be explained by the RFD of the herd. In other words, the animal must 'need' the extra feed. A cow that is producing close to her potential milk yield has a lesser 'need' for the extra nutrients than a cow that is producing less (i.e., smaller RFD). Consequently, the MR's to supplementary feed are less when unsupplemented milk yields are greater. This is also consistent with the association between PGR height and mass in the unsupplemented cows and the milk production responses to supplements.

5.3.4 The association between post-grazing residual height and mass in the pastures being grazed by unsupplemented cows (i.e., control group) and the milk production responses to supplement

In support of the hypothesis that RFD affects the milk production response to supplement DMI, when the PGR of the control group was greater, the milk production responses to supplementary feeds consumed were smaller. In my data, for every 10 mm increase in PGR height in the control group, the 4% FCM, milk yield, milk fat and milk protein yield responses to supplement DMI decreased by 45 g, 55 g, 4 g and 2.9 g, respectively (weighted analyses). The result was similar for PGR mass.

5.3.5 The effect of stage of lactation on pasture DMI and milk production responses to supplement DMI

Stage of lactation is one of the many factors affecting the voluntary DMI of the cow (Forbes, 1986) and thus the SbR when supplementary feeds are consumed by grazing dairy cows. In my data, the SbR was greatest in early lactation (34%), followed by mid (30%) and then late (17%) lactation (weighted analyses). This is consistent with the data of Ekern (1972) and Phipps et al., (1987), which identified a reduction in SbR, as SOL progressed from weeks 3 to 26. In agreement with these findings, Taylor and Leaver, (1986) reported a SbR of 0.73 in early lactation, which declined to 0.37 in later lactation.

It cannot be said, with certainty, why SOL has this effect on SbR. One potential reason could be the decline in pasture digestibility as the season progresses. In most pasture-based systems, early lactation coincides with spring and late lactation with autumn to match pasture growth profiles with animal demand (Holmes et al., 2002). Pasture digestibility is greatest in spring, and least in the summer (Roche et al., 2009). As pasture digestibility declines, the ME per kg pasture DM declines, and this can be associated with a decline in DMI (Van Soest, 1982; Holmes, 1987; Stockdale et al., 1997; Figure 5.5). Thus cows grazing lower quality pasture take longer to reach satiety and SbR increases more slowly.

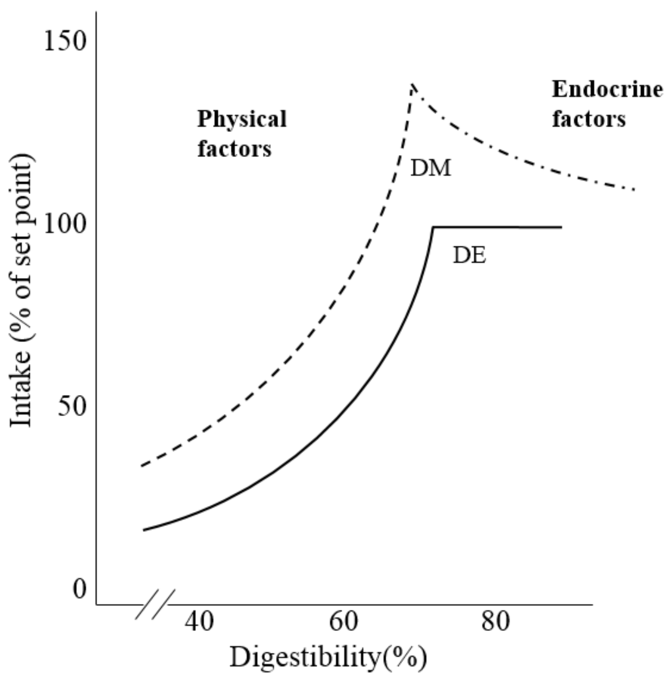

Figure 5.4: Relation between dry matter (DM) and the digestible energy (DE) of the feed ingested. Source: (van Soest, 1994)

Substitution is the primary factor affecting the MR to supplements (Stockdale, 2000b). When SbR is large, the increase in total DMI when supplements are consumed is smaller than when SbR is small (Bargo et al., 2003). In a summary of 20 experiments, Stockdale (2000) obtained a significant negative relationship between SbR and MR to supplement DMI; for every 0.1 kg DM/kg DM increase (10%) in the SbR, the marginal milk yield response declined by 0.08 kg/kg concentrate DMI.

Therefore, we would expect MR to also be smallest in early lactation (when SbR peaks) and greatest in late lactation (when SbR is at its lowest). In agreement with this expectation, the 4% FCM responses from my analyses were 0.41, 0.63 and 0.72 kg 4% FCM/kg supplement DMI in early, mid, and late lactation, respectively (non-weighted). In the weighted analyses, the greatest MR was, again, in late lactation; however, there was no difference between mid- and early lactation; the marginal 4% FCM yield responses were 0.59, 0.48 and 0.84 kg / kg supplement DM in early, mid, and late lactation, respectively. Stockdale (1999) reported the same trend; MR averaged 0.5 kg 4% FCM/kg supplement DMI in spring (i.e., early lactation), compared with 1.1 kg 4% FCM/kg supplement DMI in summer and autumn (i.e., mid and late lactation. This effect of SOL is also evident in the association between supplement DMI and pasture DMI. Pasture DMI decreased ($P = 0.06$) with supplement DMI, but the effect was much smaller in late lactation than in early and mid-lactation.

Stage of lactation did not affect the MR for the yields of milk ($P = 0.23$) or milk protein ($P = 0.44$), nor did SOL affect the association between supplementary feeding level and milk composition. However, SOL and control group milk fat% interacted to affect the milk fat% response to supplementary feed DMI. The reduction in milk fat % associated with supplement DMI changed by -0.0008% in early lactation, 0.00009% in mid lactation and -0.0008% in late lactation. The reason for this inconsistency is not known; however, the result is consistent with those reported by Penno (2002), who, in a summary of 39 experiments, demonstrated that there was little effect of SOL on the MR to supplements. Average marginal milk yield responses were 0.7, 0.6 and 0.8 kg milk/kg supplement DMI in early, mid, and late lactation, respectively.

Initially, it could seem counterintuitive, that higher-yielding cows (i.e., cows in early lactation), have greater SbR's and smaller MR's to supplements. In fact, many studies (Bargo et al., 2003; Kellaway & Porta, 1993; O'Brien et al., 1999; Stockdale & Trigg, 1985, 1989) have assumed that higher-yielding cows (in early lactation) partition a greater proportion of the feed they eat towards milk production than to body condition, and consequently should have greater MR to supplements than in late lactation. However, to achieve higher milk yields requires more energy and, therefore, higher pasture DMI. To achieve higher pasture DMI requires higher PA's (Wales et al., 1998) and, as discussed previously, it is well documented (and supported by my results) that higher PA's and pasture DMI result in greater SbR's. When SbR is lower, the relative increase in total DMI when supplements are consumed is greater. This was demonstrated in a study where total DMI was compared when cows were offered low (25 kg DM/cow/day) and high (40 kg DM/cow/day) PA's (Bargo et al., 2002). Though total DMI increased in both scenarios, the increase in the low PA (low SbR; 0.26 kg pasture/kg concentrate) treatment was 61% greater than in the high PA (high SbR; 0.55 kg pasture/kg concentrate) treatment (5.8 vs. 3.6 kg/d). . As well as influencing SbR, Stockdale (1999) analysed a series of grazing studies and identified a strong negative relationship between pasture quality and marginal FCM response to supplements. He concluded that cows grazing high quality pasture (i.e., spring pastures) had a greater ME intake and milk yields closer to their potential milk yields (i.e., a lower RFD); therefore, milk production responses will be lower. Because DMI is the factor most limiting milk production, lower pasture DMI and smaller SbR's as the season progresses and pasture quality declines, will result in comparatively higher MR to supplementary feeds, in a pasture-based system, as confirmed by the results of my analyses.

Chapter 6 Conclusions

The MR's of grazing cows to supplementary feeds vary considerably between experiments. This is not surprising considering the variation in experimental conditions (e.g. cow age and size, stage of lactation, changing environmental conditions and variation and changes in quality of pasture), not to mention changes in conditions within experiments (e.g., climatic changes, changes in pasture quality with time). Nevertheless, consistently in the analyses undertaken, substitution must be considered as a loss when feeding supplementary feeds in a pasture-based dairy system. Minimising the substitution of pasture for supplements should result in an increase in total DMI and thus improve the responses obtained from feeding supplements.

The RFD of the cow prior to consuming supplementary feeds, is the most important factor determining the magnitude of the SbR and the MR to supplement. However, the difficulty in determining the RFD of the herd makes it difficult to predict both SbR and MR. I hypothesised that the PGR height or mass could be used as a 'proxy' measure of the RFD; the results of my analyses support this hypothesis, with an increase in PGR height and mass with supplementary feeding as control pasture mass increased and a reduction in the MR to supplements. This means that more pasture was being left behind (i.e., PGR increased); however, we could not determine this with changes in DMI. The weighted analyses identified an increase in SbR with increasing PGR height and mass, while the opposite effect was evident in the non-weighted analyses.

The following table offers a summary of the key learnings. Where these learnings are not currently acknowledged or implemented by farmers, a hypothesis as to why is provided.

Key Learning	What is known	What is widely implemented	Potential reasons for the difference between what is known and implemented action
Offering grazing dairy cows supplementary feeds increases total DMI, but leads to a reduction in pasture DMI.	Cows substitute supplementary feed for pasture: for every kg supplement consumed, cows reduce time spent grazing by 10-15 minutes (Bargo et al., 2003; Sheahan et al., 2011).	Cows are offered supplement to increase DMI	Many consultants do not understand that substitution is more heavily influenced by neuroendocrine feedback measures than physical constraints and, so, cannot understand how a cow could refuse 6 to 10 kg of a bulky forage (fresh weight), when they only consume only 1.1 kg of a fresh concentrated grain
Response to supplement is less than widely believed	As a result of the increase in total DMI, milk production increases when supplements are offered; however, pasture utilisation declines due to the reduction in pasture DMI. This is evidenced by the increase in pasture residual height/mass in my analysis. The MR to supplements declines as pasture utilisation declines.	Cows are offered supplements causing post-grazing pasture residuals to rise, and pasture utilization and MR to decline.	Although models exist to predict the MR to supplementary feeds, they often assume a linear response to supplementary feeds and do not consider how pasture-level variables and grazing management influence this response. These variables contribute to the large variation in reported responses to supplements.
The RFD is a key determinant of the MR to supplements and can be estimated from post-grazing pasture residuals	The SbR increases as the RFD of the herd becomes smaller; this causes more pasture being left ungrazed. The PGR is reflective of the RFD; thus, the MR will be greater when the PGR is lower.	Post-grazing pasture residuals are not frequently used in decision making surrounding supplementary feed. Rather farmers aim to increase milk yield from the feeding of supplements, without considering pasture utilisation.	In general, farmers and their advisors do not understand the concept of RFD and how this affects the MR to supplementary feeds.

Table 15: A comparison of key learnings from the study and common industry practices in New Zealand.

A practical application of these results would be for farmers to use the change in PGR height when feeding supplements, to estimate likely MR to supplements. The PGR is reflective of the RFD, thus the MR will be greater when the PGR is lower. In New Zealand, PGR mass of 1500 kg DM ha^{-1} (35 mm height measured to ground level) or more, are associated with low MR to supplements and PGR mass of less than 1400 kg DM ha^{-1} (30 mm height measured to ground level) are associated with high MR to supplements (Roche & White, 2012; Figure 6.1).

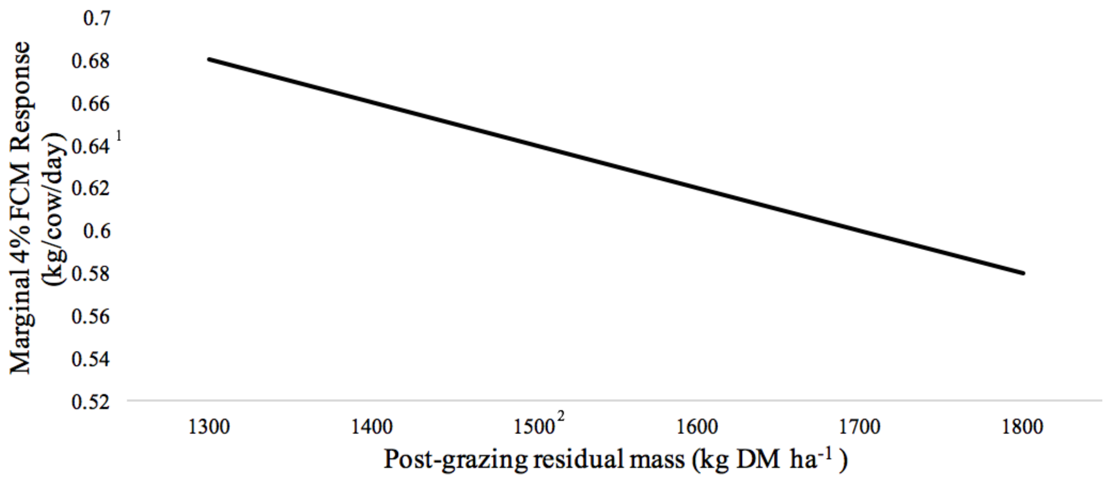

Figure 6.1: An example of how post-grazing residual mass may be used to predict marginal milk production responses to supplement. This is based on the response functions from my analyses;[1]0.64 kg 4% FCM/cow/day is the average marginal response generated from my analyses [2]1500 kg DM/ha is the recommended as being the optimal compromise between the requirements of the plant and the requirements of the animal (Ganche et al., 2013; Roche et al., 2017).

Based on my data, pasture height, which exhibited a stronger relationship with marginal milk production responses than pasture mass, is the preferred/recommended pasture level variable to predict the RFD. Furthermore, for practicality in some situations, pasture height, which is measured by a plate meter, may be may be a more accurate variable, than a poorly calibrated assessor of pasture mass.

Chapter 7 Limitations

As with any study of this nature, it is important to consider the limitations of the approach, and the data used.

The results and the conclusions that can be inferred from the data analyses are limited by the lack of reporting of pasture management variables in nutrition experiments (e.g., pre-grazing height and mass and PGR height and mass). The reporting of pasture management-related variables is an important requirement to allow us to better understand reasons for the variability in MR to supplements, where the substitution of the supplement for pasture is a key reason for variability. In addition, even when pasture variables were reported, there is a lack of consistency in how these measurements were undertaken and/or reported. For example, the methodology for determining pasture mass varied widely worldwide, due, particularly, to cutting methodology or the estimated height.

Because the methodology for measuring pasture mass is highly variable between countries, the analyses included studies where pasture mass and pasture allowance were estimated at ground level or at 30, 35, 40, or 50 mm. Bulk sward density decreases with increasing height, with the greatest sward bulk density at ground level (Pérez-Prieto et al., 2013). Consequently, inconsistency in methodology led to large variability in estimates of pasture mass and reduced my ability to use much of the data presented. For example, when measured at ground level, herbage mass ranges from 3,000 to 6,000 kg DM ha^{-1}; however, when measured above 40 to 50 mm, this range is 1,000 to 3,000 kg of DM ha^{-1} (Perez-Ramirez et al., 2009).

Within each reported study, pre-grazing pasture mass was measured in the same way as PGR mass; thus, the effect of supplementation on the PGR (i.e., the marginal response) within a study (which was the focus of my research) was consistent; but due to insufficient information in the Materials and Methods, pasture mass and height could not be standardised across all the studies in the database. To enable predictions on the effect of supplement DMI on PGR mass under different conditions, it would be necessary to standardise pasture mass and height across all studies and not just within study. As the analyses stands, the effect of supplementation on pasture residual assumes that the effect of supplementation is the same at a 1500 kg DM residual as a 2000 kg DM residual, which is unlikely to be true. This is a limitation of the data and the results.

There are also limitations in a meta-analysis. One of the most common criticisms against meta-analysis is publication bias (Schmidt & Hunter, 2015); this exists when the meta-analysis consists of data from only published studies. This is because studies that show a 'positive' result are more likely to be published than those that do not (Lean et al., 2009). To ensure the validity of the results, a meta-analysis must evaluate bias in the identification and selection of studies that will be included or excluded. Published studies are more likely to include results that have larger effect sizes and are statistically significant, causing an upward bias of the effect size estimates from meta-analysis (Schmidt & Hunter, 2015). My dataset only consists of data from published studies; however, I don't believe that publication bias is likely to be a significant concern. This is because the focus of the meta-analysis was on PGR height or mass; these measurements were not central to the primary studies from which the data are collected. Rather, PGR height and mass measurements tend to be reported on an incidental basis (i.e., as a supplementary measurement required to estimate the pasture intake of the cows in experiments that focus on the marginal milk production response to supplement). However, it is possible that a bias exists in published supplementary feeding studies (and, therefore, in my analyses), as studies reporting high responses to supplements are more likely to be published than those reporting low responses. Because lower PGR's are associated with higher MR's to supplementary feed, the data may have lower PGR's , rather than reflect real situations on pastoral dairy farms. Furthermore, pasture management would, likely, be of high quality in most studies and, therefore, I may not have data from the upper end or lower end of the PGR range. That said, the PGR height in the studies used ranged from 13 mm to 120 mm and, therefore, reflect the majority of likely situations in temperate grazing systems. Nevertheless, extrapolation of these results to predict MR's outside the range of these data, should be considered carefully.

Finally, the lack of SE's reported in individual studies also limits the conclusions that can be inferred from this analyses. The pasture DMI response to supplementary feed was completely different in the weighted and non-weighted analysis. This emphasizes the inconsistency of the data as the removal of some studies resulted in a contradictory result. Ideally every study would report SE's of every variable managed.

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Appendices

Appendix 1: Summary of experiments included in the analyses of marginal responses of grazing cows to supplementary feed

Appendix 1: Summary of experiments included in the analyses of marginal responses of grazing cows to supplementary feed

Reference		**Cows**[1]		**Pasture**[2]		**Supplement**[3]		**MR**[4]
Author	Country	DIM	Milk	Type	PA	Type	DMI, kg/d	kg 4% FCM / kg supplement
Bargo et al., 2002	USA	101	45.8	SB/OG/KB	26.7	Ground dry shelled corn based concentrate	8.6	0.92
					48.9		8.7	0.61
Burke et al., 2008	Ireland	140	28.5	PR	14.6	Maize silage	3.2	1.08
						High CP concentrate	4	0.74
						Low CP concentrate	4.9	1.05
Chaves et al., 2006	NZ	156	14.3	PR/WC	18	Sulla silage	5.2	-0.05
					25	Maize silage	5.5	-0.02
Delaby et al., 2001	France	177	28-31	PR	12.1	Pelleted concentrate	1.8- 5.37	0.88
					15.8		1.81-5.28	0.86
					16.6		2.63-5.36	0.79
					19.6		2.65-5.35	0.68
					16.5		2.65-5.34	0.79
					21		2.63-5.27	0.75
Dillon et al., 1997	Ireland	26-38	26.8	PR	19.7	High-energy concentrate	2-4	0.29

[1] Pre-experimental days in milk and milk production (kg/day)

[2] Pasture type and allowance (PA); BG = Bermuda grass (*Cynodon dactylon*); RP= Rhizoma Peanut (*Arachis glabrata*); PR= perennial ryegrass (*Lolium perenne*); PT= rough bluegrass (*Poa trivialis*); WC = white clover (*Trifolium repens*); T= timothy (*Phleum pratense* L.); MF= meadow fescue (*Festuca pratensis* Huds.); SB= smooth bromegrass (*Bromus inermis* L.); OG= orchard grass (*Dactylis glomerata*); KB= kentucky bluegrass (*Poa pratensis* L.); AG= (*Agrostis stolonifera);* PAS= paspalum (Paspalum dilatatum); A= alfalfa (Medicago sativa); RC= red clover (*Trifolium pratense* L.)

[3] Supplement type and dry matter intake (DMI)

[4]Marginal response to supplement DMI.

Appendix 1 (continued). Summary of experiments included in the analyses of marginal responses of grazing cows to supplementary feeds

Reference		Cows		Pasture		Supplement		MR
Author	Country	DIM	Milk	Type	PA	Type	DMI, kg/d	kg 4% FCM / kg supplement
Fike et al., 2003	USA	126	NA	BG	9.7	Hominy + Soybean hulls based concentrate	4.2-7.9	0.66
				BG	9.7		4.2-7.9	0.76
				RP	5.6		5-8.6	0.38
				RP	5.6		5.1- 8.4	0.52
Grainger and Mathews, 1989	Australia	21	19	PR/CF/WC	33.2	Grain-based pelleted concentrate	3.2	0.13
					17.1		3.2	0.55
					7.6		3.2	0.55
Kennedy et al., 2007	Ireland	14	22.3	PR	13.3	Concentrate	4	1.29
					15.9		4	0.73
					19		4	0.93

[1] Pre-experimental days in milk and milk production (kg/day)
[2] Pasture type and allowance (PA); BG = Bermuda grass (*Cynodon dactylon*); RP= Rhizoma Peanut (*Arachis glabrata*); PR= perennial ryegrass (*Lolium perenne*); PT= rough bluegrass (*Poa trivialis*); WC = white clover (*Trifolium repens*); T= timothy (*Phleum pratense* L.); MF= meadow fescue (*Festuca pratensis* Huds.); SB= smooth bromegrass (*Bromus inermis* L.); OG= orchard grass (*Dactylis glomerata*); KB= kentucky bluegrass (*Poa pratensis* L.); AG= (*Agrostis stolonifera);* PAS= paspalum (Paspalum dilatatum); A= alfalfa (Medicago sativa); RC= red clover (*Trifolium pratense* L.)
[3] Supplement type and dry matter intake (DMI)
[4] Marginal response to supplement DMI.
[5] NA = not available

Appendix 1 (continued). Summary of experiments included in the analyses of marginal responses of grazing cows to supplementary feeds

Reference		**Cows**[1]		**Pasture**[2]		**Supplement**[3]		**MR**[4]
Author	Country	DIM	Milk	Type	PA	Type	DMI, kg/d	kg 4% FCM / kg supplement
King et al., 1990	Australia	35	22.8	PR/WC	47.6	High-energy concentrate	3.3	0.26
					47.6	High-energy concentrate + fatty acids	3.8	0.76
McEvoy et al., 2008	Ireland	18	29.8	PR	13	Ground citrus pulp and barley based concentrate	3-6	0.76
					17		3-6	0.51
Penno et al., 2006	NZ	66	NA	PR/WC	25	Maize grain	3.2-4.6	0.84
						Balanced ration		0.17
		157			37	Maize grain	3.7-3.8	0.74
						Balanced ration		0.94
		251			30	Maize grain	3.7-4.9	0.89
						Balanced ration		0.66
		52			30	Maize grain	4.6-6.2	-0.45
						Balanced ration		-0.52
		126			35	Maize grain	5.8	0.4
						Balanced ration		0.58

[1] Pre-experimental days in milk and milk production (kg/day)

[2] Pasture type and allowance (PA); BG = Bermuda grass (*Cynodon dactylon*); RP= Rhizoma Peanut (*Arachis glabrata*); PR= perennial ryegrass (*Lolium perenne*); PT= rough bluegrass (*Poa trivialis*); WC = white clover (*Trifolium repens*); T= timothy (*Phleum pratense* L.); MF= meadow fescue (*Festuca pratensis* Huds.); SB= smooth bromegrass (*Bromus inermis* L.); OG= orchard grass (*Dactylis glomerata*); KB= kentucky bluegrass (*Poa pratensis* L.); AG= (*Agrostis stolonifera);* PAS= paspalum (Paspalum dilatatum); A= alfalfa (Medicago sativa); RC= red clover (*Trifolium pratense* L.)

[3] Supplement type and dry matter intake (DMI)

[4] Marginal response to supplement DMI.

Appendix 1 (continued). Summary of experiments included in the analyses of marginal responses of grazing cows to supplementary feeds

Reference		**Cows**[1]		**Pasture**[2]		**Supplement**[3]		**MR**[4]
Author	Country	DIM	Milk	Type	PA	Type	DMI, kg/d	kg 4% FCM / kg supplement
Penno et al., 2006 (cont.)	NZ	215			32	Maize grain	5.9-6.5	0.26
						Balanced ration		0.37
Reis and Combs, 2000	USA	84	41.6	A/RC/OG/SB	26.7	Ground dry shelled corn based concentrate	5-10	0.15
Sairanen et al., 2006	Finland	105	35	T/MF	21	Barley based concentrate	3-9	0.65
		131	30.8		25		3-9	0.55
		115	34		25		3-9	0.32
Stakelum, 1986	Ireland	204	NA	AG/PR/PT	21.4	95% Barley, 5%Molasses	3.2	0.13
					14.3		3.2	0.51
Stockdale, 1996	Australia	213	14.9	WC	19	Maize Silage	4.4	0.79
					39		4.3	0.2
Stockdale, 1997a	Australia	110	28.2	WC	21	Maize Silage	4.8	0.44
		154	24.2		22		4.6	0.28

[1] Pre-experimental days in milk and milk production (kg/day)

[2] Pasture type and allowance (PA); BG = Bermuda grass (*Cynodon dactylon*); RP= Rhizoma Peanut (*Arachis glabrata*); PR= perennial ryegrass (*Lolium perenne*); PT= rough bluegrass (*Poa trivialis*); WC = white clover (*Trifolium repens*); T= timothy (*Phleum pratense* L.); MF= meadow fescue (*Festuca pratensis* Huds.); SB= smooth bromegrass (*Bromus inermis* L.); OG= orchard grass (*Dactylis glomerata*); KB= kentucky bluegrass (*Poa pratensis* L.); AG= (*Agrostis stolonifera);* PAS= paspalum (Paspalum dilatatum); A= alfalfa (Medicago sativa); RC= red clover (*Trifolium pratense* L.)

[3] Supplement type and dry matter intake (DMI)

[4] Marginal response to supplement DMI.

[5] NA = not available

Appendix 1 (continued). Summary of experiments included in the analyses of marginal responses of grazing cows to supplementary feeds

Reference		**Cows**[1]		**Pasture**[2]		**Supplement**[3]		**MR**[4]
Author	Country	DIM	Milk	Type	PA	Type	DMI, kg/d	kg 4% FCM / kg supplement
Stockdale, 1997b	Australia	234	15.4	PAS/WC	21	Maize Silage	5	1.15
				WC	21		4.9	0.64
(Stockdale, 1999a)	Australia	NA	NA	PR/PAS/WC	42	75% Barley-25% grain pellet	4.8	0.82
				PR/PAS/WC	42		4.7	1.04
(Stockdale, 1999b)	Australia	10	29.9	PR/PAS/WC	30	75% Barley-25% grain pellet	4.6	0.43
		106	30	PR/PAS/WC	30		4.9	0.55
		112	25.7	PR/PAS/WC	30		4.9	1.18
		165	19.3	PR/PAS/WC	30		3	1.17
		128	30.6	PR/PAS/WC	40		4.7	0.49
		180	25.1	PR/PAS/WC	40		4.8	0.98
		229	21.6	PR/PAS/WC	40		4.9	0.94

[1] Pre-experimental days in milk and milk production (kg/day)

[2] Pasture type and allowance (PA); BG = Bermuda grass (*Cynodon dactylon*); RP= Rhizoma Peanut (*Arachis glabrata*); PR= perennial ryegrass (*Lolium perenne*); PT= rough bluegrass (*Poa trivialis*); WC = white clover (*Trifolium repens*); T= timothy (*Phleum pratense* L.); MF= meadow fescue (*Festuca pratensis* Huds.); SB= smooth bromegrass (*Bromus inermis* L.); OG= orchard grass (*Dactylis glomerata*); KB= kentucky bluegrass (*Poa pratensis* L.); AG= (*Agrostis stolonifera);* PAS= paspalum (Paspalum dilatatum); A= alfalfa (Medicago sativa); RC= red clover (*Trifolium pratense* L.)

[3] Supplement type and dry matter intake (DMI)

[4] Marginal response to supplement DMI.

[5] NA = not available

Appendix 1 (continued). Summary of experiments included in the analyses of marginal responses of grazing cows to supplementary feeds

Reference		**Cows**[1]		**Pasture**[2]		**Supplement**[3]		**MR**[4]
Author	Country	DIM	Milk	Type	PA	Type	DMI, kg/d	kg 4% FCM / kg supplement
(Stockdale, 2000b)	Australia	21	25-30	PR/WC	40	Pasture Hay + Pelleted Concentrate	4.7	0.29
		46		PR/PAS/WC	38.5		4.1	0.29
(Stockdale & Trigg, 1985)	Australia	240	10	PAS	15.4	High-energy concentrate	1.8-6.3	0.58
					26.2	High-energy concentrate	1.8-6.2	0.54
(Stockdale & Dellow, 1995)	Australia	87	NA	WC	20	Maize Silage	5	0.56
		216			21		4.2	0.97
		100			23		3.7	0.5
		112			22		3.4	0.02
		183			20		3.8	0.5
		172			20		3.8	0.83
		217			20		4.4	0.79
		106			21		4.8	0.44
		152			23		4.6	0.28
		222			22		4.9	0.64

[1] Pre-experimental days in milk and milk production (kg/day)

[2] Pasture type and allowance (PA); BG = Bermuda grass (*Cynodon dactylon*); RP= Rhizoma Peanut (*Arachis glabrata*); PR= perennial ryegrass (*Lolium perenne*); PT= rough bluegrass (*Poa trivialis*); WC = white clover (*Trifolium repens*); T= timothy (*Phleum pratense* L.); MF= meadow fescue (*Festuca pratensis* Huds.); SB= smooth bromegrass (*Bromus inermis* L.); OG= orchard grass (*Dactylis glomerata*); KB= kentucky bluegrass (*Poa pratensis* L.); AG= (*Agrostis stolonifera);* PAS= paspalum (Paspalum dilatatum); A= alfalfa (Medicago sativa); RC= red clover (*Trifolium pratense* L.)

[3] Supplement type and dry matter intake (DMI)

[4] Marginal response to supplement DMI.

[5] NA = not available

Appendix 1 (continued). Summary of experiments included in the analyses of marginal responses of grazing cows to supplementary feeds

Reference		Cows[1]		Pasture[2]		Supplement[3]		MR[4]
Author	Country	DIM	Milk	Type	PA	Type	DMI, kg/d	kg 4% FCM / kg supplement
(Suksombat, Holmes, & Wilson, 1994)	NZ	111	12.4	PR/WC	63	High-energy concentrate	2.7	0.88
(Wales, Doyle, Stockdale, & Dellow, 1999)	Australia	126	25.2	PAS/PR/WC	27	Cereal-grain based concentrate	5	1.14
				PAS/PR/WC	48		5	0.8
				PAS/PR/WC	27		5	1.12
				PAS/PR/WC	48		5	0.79
(Wales et al., 2001)	Australia	49	25.2	PR/WC	19	Fibre Pellet	2.4	0.5
						Fibre Cube	2.1	-0.35
						Grain Pellet	4.5	0.98
						Grain + Fibre Pellet	7.2	0.62
						Grain + Fibre Cube	7.4	0.46
(Woodward et al., 2006)	NZ	146	15.6	PR/WC		Pasture silage	5	0.2
						Maize silage	4.6	0.17
						Lotus silage	5	0.71
						Sulla silage	3.6	0.25

[1] Pre-experimental days in milk and milk production (kg/day)

[2] Pasture type and allowance (PA); BG = Bermuda grass (*Cynodon dactylon*); RP= Rhizoma Peanut (*Arachis glabrata*); PR= perennial ryegrass (*Lolium perenne*); PT= rough bluegrass (*Poa trivialis*); WC = white clover (*Trifolium repens*); T= timothy (*Phleum pratense* L.); MF= meadow fescue (*Festuca pratensis* Huds.); SB= smooth bromegrass (*Bromus inermis* L.); OG= orchard grass (*Dactylis glomerata*); KB= kentucky bluegrass (*Poa pratensis* L.); AG= (*Agrostis stolonifera);* PAS= paspalum (Paspalum dilatatum); A= alfalfa (Medicago sativa); RC= red clover (*Trifolium pratense* L.)

[3] Supplement type and dry matter intake (DMI)

[4]Marginal response to supplement DMI.

[5] NA = not availabl